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THE EMPLOYMENT OF JET V-STOL AIRCRAFT AT SEA

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SUMMARY

The means by which the Royal Navy will continue to operate fixed-wing aircraft at sea is by employing VTOL, or, given an aid to take-off, STOVL aircraft. The aid being brought into service is the Skijump, which permits a large increase in payload over unassisted VTOL. The effectiveness of skijump increases with its exit angle up to about 40^{o}, but other considerations of size and ungainliness set a practical limitation nearer to 20^{o}.

The endspeeds required for ballistic launch off a skijump could be achieved or enhanced by the use of assistance by catapult or rocket motor. Both of these would call for the initiation of programmes of full research and development, while the skijump, capable of conferring equivalent performance if it is long enough, already exists.

The smallest number of aircraft in an airgroup able to keep up a useable flying task is three. A vessel big enough to mount three aircraft together with the gear necessary to support and arm them would be big enough to mount a skijump as well. Its size is dictated too by the sea conditions in which it is expected to keep operational.

The vessel in question should be a displacement ship, either conventional (e.g. large frigate) or unconventional (e.g. Small Waterplane Area Twin Hull). There is no role here for either hovercraft or hydrofoil.

Commitment to the skijump in the ship means commitment to vectored-thrust as a means of propulsion in the next aircraft. When specified it must be compatible with existing skijump decks, and it should be single-engined. Its targets for Reliability and Maintainability must be wholly related to the Availability called for, and must be given equal prominence with performance.

'What do you know about this business'
the King said to Alice.

'Nothing' said Alice.

'Nothing whatever?' persisted the King.

'Nothing whatever,' said Alice.

'That's very important,' the King said.

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INTRODUCTION

Background

The first seeds of this study were sown in 1977. At that time there was taking place a renewal of interest in the possibilities of employing vertical-takeoff aircraft at sea on three separate and independent fronts:-

a. In America the United States Navy was becoming concerned that the cost of persisting with conventional catapult-launched fixed-wing aircraft at sea might be getting out of hand, and it was inviting proposals from the aircraft industry for designs of VTO aircraft capable of taking over the role of its current aircraft types by the turn of the century and so offsetting, at least partially, the cost of building a new generation of nuclear-powered aircraft carriers.

b. In Russia the Soviet Navy, which had been quiet in the VTO field since displaying the Yakolev 'Freehand ' at the Demodedovo Air Parade in 1967, was now seen to be equipping its new and first aircraft carriers with the successor to that aircraft and one that operated in the VTO mode exclusively.

c. In Great Britain the first practical demonstrations of the Skijump passive launching aid had begun, and it came to be realised that with this simple aid to takeoff the potential of the Sea Harrier might be far greater than had previously been supposed.

The entry of the Sea Harrier into service with the Royal Navy had been regarded as a valiant but last-ditch attempt to get back into the business of operating fixed-wing aircraft at sea after the 'Ark Royal', with her fighter, strike and AEW aircraft, had paid off at last. Now it became recognised as offering the prospect of something more. Now, it could well mark the first step into a whole new era of Naval Aviation, with the Royal Navy, freed of other fixed-wing distractions, perfectly placed to pioneer the route for the rest of the world's air oriented Navies to follow. But it could also represent the last flicker of life in the manned Naval strike fighter before it gave way to an already overdue new age of air warfare to be fought with guided missiles and RPVs.

At this time the energies of the relevant departments of the Ministry of Defence, the Royal Aircraft Establishments and the Aerospace Industry were already dedicated to the search for solutions to the problems posed by the Harrier aircraft itself together with its support and operations, and the Ministry of Defence began to feel slightly uneasy that in concentrating its resources in this direction alone it might overlook some aspect of the VTO activity that could, if identified in time, repay more attention.

What was needed, it felt, was that someone should be tasked to take a broader look at the Sea Harrier project, survey the equipment existing or coming into existence associated with VTO aircraft, and recommend which ones to pursue and which to discard, all as part of a total investigation of what the VTO aircraft has to offer a compact and concentrated Navy, and where it might lead. It felt too, that with the Defence Establishment already working along predetermined lines, such a survey would be carried out most advantageously from a position outside the Service environment, albeit from a Service standpoint.

The idea of fielding such a project was first voiced by the Deputy Controller of Aircraft (B) in the Procurement Executive, an appointment held by the Senior Naval Air Engineer Officer in the Ministry of Defence. He considered that the study should be conducted by a serving Naval Officer of the Engineering Branch specialised in Aviation, and that an ideal venue for this undertaking would be the Cranfield Institute of Technology, a College with long-established professional links with the Royal Navy but one owing no allegiance to any particular military or technological line of thought. This proposal was circulated in November 1977, (Ref.1), to those bodies in the Ministry of Defence most likely to be concerned, namely The Flag Officer, Naval Air Command, the Director of Naval Air Warfare, the Head of Aircraft Department (Navy), the Director of Harrier projects (MOD.PE), together with the Director of Naval Officers' Appointments, (Engineer).

All these Departments agreed to support the scheme, and following a series of meetings there was produced a statement of Terms of Reference for the study (Ref.2). The Director of Naval Officers' Appointments was requested to provide a suitable candidate to take it in hand.

The job description called for a Lieutenant-Commander or Commander (A/E), with Squadron, Sea,and Project Management experience,and thought to be intellectually capable of the work.

Satisfying at least half of these criteria, the Writer was invited to undertake the study in 1978, was formally appointed to DNAW additional for duty outside M.O.D. for V-STOL study for 2 years at Cranfield (Ref.3), and took up his burden in January 1979.

Terms of Reference

The Terms of Reference put together by DNAW, DGA(N) and DCA are shown in full at Annex A, and may be summarised as follows:

1. To investigate how the Sea Harrier might be able to operate from ships other than Aircraft Carriers (Note)
2. To investigate how the aircraft might be assisted in its launch, e.g. by steep skijump, rocket assistance, catapult.
3. To consider how the selected launch aid might interface with the ship.
4. To consider how the aircraft might be recovered on board.
5. To study the question of logistic support.
6. To determine the level of Availability that might be expected.

While this statement of requirements is clear and unambiguous, there hovers behind it the essence of the original question; should the Navy commit itself to the combination of Sea Harrier and Skijump as embodying the best approach to meeting the challenge of V-STOL? Are we going the right way?

The Study

The project having been set as a series of individual exercises it has been handled in a similar manner, the subject being broken into a sequence of topics each one of which has been dealt with separately. Each is self-contained with its own Introduction, Summary, Text, Conclusion and Appendices, and the initial drafts of all but the last have been submitted to DCA, (whose title changed to DGA(B) during the early stages of the investigation), on completion as a series of progress reports. Here they are presented all together in a completed state, the earlier ones having undergone extensive revision as the study has progressed and as external developments have continued.

In order that the theme of the study may maintain a continuous flow the separate topics listed in the Terms of Reference have been dealt with in an order different from the original. This Paper now comprises seven parts as follows:

Note: This definition of the task exempts the Vosper-Thorneycroft 'Harrier Carrier'. This proposed lightweight aircraft carrier is already well-documented, and the findings of the study where relevant are fully applicable to it.

Part 1. The State of the Art

This introductory study sets the scene by surveying the history of jet V-STOL flight from its earliest days up to the present. It introduces the strategic factors, the rise, fall and subsequent resurgence of interest in VTO aircraft, and acts as a prelude to a study of the technicalities of the subject covering the qualitative problems of design, propulsion and control specific to aircraft of this type. It concludes with an unclassified summary of the substance and findings of Parts 2-7 inclusive.

Part 2. The Skijump

Here a simple set of equations of motion for an aircraft undergoing a ballistic launch are derived, and a basic outline model developed on which the changes are rung of variation in aircraft weight, nozzle angle, skijump exit angle and end speed, so that the most effective combination of these may be identified and a relationship determined between aircraft weight at takeoff and launch speed required. This relationship is taken as a starting point for Part 3.

Part 3. Getting Airborne

All methods of getting a vectored-thrust aircraft off the deck are considered, vertical takeoff, rolling takeoff and takeoff with assistance. No available method is rejected arbitrarily even though it is clearly unsuitable for application in the circumstances obtaining at present. The object is to explore and chart every approach to the problem, producing an unbiased record that can be referred to should the circumstances change.

Part 4. Availability

First it must be decided what the word means, and then a model developed to show how Availability, as defined now, relates to Maintainability and Reliability. Representative values of these latter measures taken from experience of aircraft in current service are used to produce figures for the sort of achievement that small detachments of aircraft might be expected to sustain.

Part 5. Support and Logistics

Part 4 having shown that a worthwhile rate of flying could be achieved given values of Maintainability and Reliability of the right order, the resources of Manpower, Consumables and Weaponry necessary to sustain these values are estimated, together with their impact on the vessel which is to carry them.

Part 6. The Ship

In Parts 2, 3, 4 and 5 an aviation package has been compiled. Part 6 is devoted to a study of the type of surface vessel to which this package could be attached. Selection of the type of ship is also influenced by the nature of the conditions in which it is meant to operate, so these are considered, along with the influence they will have on how the aircraft will be recovered on board.

Part 7. The Next Aircraft

A byproduct of the study so far has been the emergence of a set of characteristics, not necessarily lacking in the Sea Harrier, which ought to be embodied in the aircraft to succeed it. In this final part they are all brought together and recommendations are made of how they should be incorporated in the next Naval Staff Requirement should there be one.

Security Classification

These introductory pages together with Part 1 of the study 'The State of the Art', are drawn from information that is freely available to all, and therefore they are rated 'Unclassified'.

In writing the body of the text, however, it has been necessary to refer to material such as performance and reliability data for current aircraft types, together with other information of limited circulation, so Parts 2 through 7 must be classified 'Restricted'. Their main points are summarised in an unclassified form as a final section to Part 1.

The copies of this Thesis retained by the Cranfield Institute of Technology must therefore be presented in two volumes, one of each classification. Those forwarded to the Ministry of Defence, where classified material is the norm, show the higher classification.

Units

Where units of measurement have been used they are the ones by which aircraft of the Royal Navy are flown and operated, namely pounds, feet, nautical miles and knots.

Level of Study

Any one of the topics detailed in the Terms of Reference could form the subject of a major research endeavour on its own and indeed some of them already do. Inevitably then in some cases here the level of treatment has been such as to scratch the surface only barely, but nevertheless, it is hoped deeply enough for the nature of the substance to be determined. As stated previously, research and development into some topics at issue is already in hand at a high professional level. Where this is so it would obviously be futile to attempt to replicate and overtake that research, and so in such cases, the development of a system of deck approach, for instance, or the redesign of the response of an undercarriage shockabsorber, the text is limited to a record of what has been done.

These exceptions aside, the policy of the writer has been to attempt to develop every subject from first principles, making minimal reliance on data drawn from other sources other than as waypoint checks along the route. That way all subjects have been developed to a consistent level, and by surveying the pattern which emerges an attempt has been made to discern and identify sufficient threads in common to support an authoritative conclusion.

It is hoped that this work will help to give the Royal Navy the assurance that in adopting the combination of skijump and vectored thrust aircraft as its choice of equipment with which to enter an era of STOVL aircraft at sea, it is taking the right step in the right direction. It is hoped too that it may act as useful introductory reading, indeed as a basic instruction manual, for those other friendly Navies who are contemplating setting off in the same direction.

M.J.Kinch
Lieutenant-Commander (M)(A/E)(P)
Royal Navy.

January, 1981

REFERENCES

1. MOD DCA(B) letter ZQ/221/01 dated 17 November 1977.

2. Annex A to MOD letter ZQ/221/01 dated 21 July 1978.

3. Officers' Appointments List 64/78 dated 30 August 1978.

ANNEX A

Full Terms of Reference

STUDY ON USE OF V-STOL AIRCRAFT AT SEA

Specification

1. Starting from the current concepts of operation of Sea Harrier FRS Mk 1 from CAH/CVS, consider how the benefits which the Navy obtains from fixed wing V-STOL might be increased by operating from other ships, including RFAs, taking account of any envisaged Sea Harrier replacement and bearing in mind any associated performance increase or growth in weight and size.

2. Within the framework defined above, consider how the required launch weights might be achieved on small ships by the use of launch augmentation devices such as:

   a. Ski-jump with large exit angle.

   b. Launch from inclined ramp with rocket assistance

   c. Launch from inclined ramp with catapult, etc.

3. Consider the provision on small ships of the optimum launch facility defined in 2 above and the feasibility of operation of this device with respect to undercarriage/ airframe strength and limitations.

4. Consider the provision of aids for recovery.

5. Consider the problems of logistic support for the operation of Sea Harrier and its replacement.

6. Within the expected reliability and maintainability of the Sea Harrier FRS Mk 1 and the results of 5 above, determine the expected aircraft availability during operations from small ships.

7. During the study if any factor emerges which could increase the operational capability of V-STOL aircraft at sea, then this should be explored, if necessary in preference to other items above.

ACKNOWLEDGEMENTS

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The Royal Aircraft Establishment, Farnborough.

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The Maritime Tactical School, HMS 'Dryad'.

The Naval Aircraft Technical Evaluation Centre, HMS 'Daedalus'.

The Rocket Motor Establishment, Ministry of Defence, Westcott.

The Royal Corps of Naval Constructors.

Yarrow Shipbuilders Limited, Scotstoun, Glasgow.

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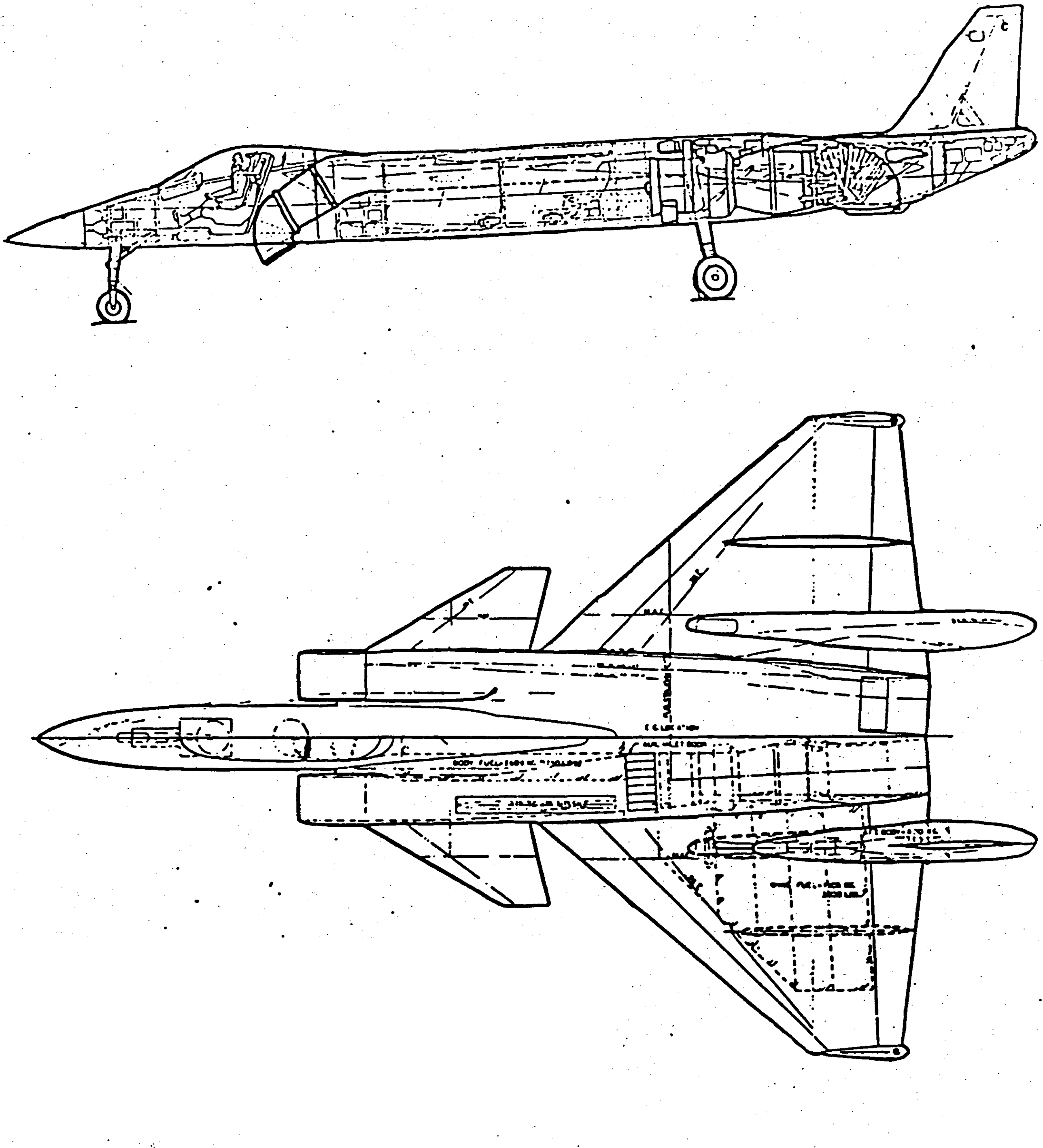
CRANFIELD INSTITUTE OF TECHNOLOGY

DEPARTMENT OF AIRCRAFT DESIGN

THE EMPLOYMENT OF JET V-STOL AIRCRAFT AT SEA

PART 1

JET V-STOL : THE STATE OF THE ART



Frontispiece: Fig.01 - Northrop submission for V-STOL fighter/attack aircraft

JET V-STOL - THE STATE OF THE ART - AUTUMN 1980

SUMMARY

For twenty-five years jet V-STOL has been a technology largely without an application. There are now indications in at least three major Navies, those of the USA, the USSR, and Great Britain, that a role is being found for it at last. In the Royal Navy in particular, VTOL offers the only route to continuing operations of fixed wing aircraft at sea.

The requirements for engines, their intakes, jet pipes and installations are very different from those for conventional aircraft, and a new form of flying control system has had to be devised to handle flight in the hover. The reasons for those differences, and the advantages and disadvantages of some likely solutions are discussed.

The prominent jet VTOL experimental and ground attack fighter aircraft schemed and produced during the last twenty-five years are briefly described. So too are the latest types currently known to be under consideration, and the developments required to make them realisable in practise.

'Explain all that,' said the Mock Turtle.

'No, no. The adventures first,' said the Gryphon in an impatient tone. 'Explanations take such a dreadful time.'

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JET V-STOL : THE STATE OF THE ART

INTRODUCTION

This paper forms the first part of a study commissioned by the Director of Naval Air Warfare, Ministry of Defence UK on the subject of the future use of VTOL aircraft at sea, particularly in sub-capital ships. It is intended to lead in to that study and should also stand on its own as a survey of the position of jet VTOL aircraft today, how they have developed, how they may be best used in a defence activity, and where developments now being explored may lead.

It is confined to pure VTOL jet aircraft. Other methods of V-STOL exist of course and are already widely employed. The helicopter, for instance, as an established V-STOL aircraft needs no further introduction, and while variations on the theme of rotary wing as a lifting medium exist, and have been demonstrated, their application is seen to be best suited to anti-submarine, transport and auxiliary aircraft tending toward the larger aircraft types, rather than high performance Fighter/Ground Attack types which are our concern here.

While touching on the subject of rotary wing aircraft, it is worth heeding that there are many systems developed and available, which offer considerable advances over the performance of the current generation of helicopters. Systems like the circulation-controlled rotor, the stowed rotor, the advancing blade concept have been on offer for many years, but there has been no rush to adopt them. The cautious helicopter operator, be he Military or Civil, seems to prefer to stick to the type of aircraft he knows rather than face having to learn to manage a new technology, regardless of the advantages it may offer him. As we shall see, a similar attitude marks the posture of the fixed-wing operator when confronted with the innovation of jet-VTOL.

The development of Jet VTOL over the past twenty-five years has been ably chronicled in the pages of the periodical journals of the aviation and military professions, and it is from these pages that the greater part of the following material is drawn. My aim has been to cover the whole subject thoroughly but not deeply. A lot of the material touched on merits study in greater depth than I have afforded it, so along with the list of References at the end of this paper there is a bibliography identifying the most important articles and features on each particular topic. It is hoped that these pointers may be of use to students in search of greater detail. None of the material used is classified.

In an attempt to keep separate the elements of military consideration, engine development, design and control, and history that characterises most writings on VSTOL (and other) aircraft, this paper is presented in five main sections as follows:

Section 1 - The Military Customer

Section 2 - Power for VSTOL

Section 3 - Control, stability and inlet/exhaust design

Section 4 - Noteworthy aircraft types

Section 5 - The present and the future

SECTION 1. THE MILITARY CUSTOMER relates the history of the VTOL aircraft as a procured weapon and shows that, until recently, it has always developed under the shadow of its conventional counterpart. It goes on to consider the circumstances that may bring the VTOL fighter back into the foreground of Naval planning, and what its role might be.

SECTION 2. POWER FOR V-STOL discusses the methods available for pure jet vertical takeoff, describes their development and considers their relative advantages and disadvantages.

SECTION 3. CONTROL, STABILITY AND INTAKE-EXHAUST DESIGN deals with the problems of introducing a flying control system to an aircraft with no airflow for conventional controls to bite on. It also describes the interactions between intake and exhaust flow and the aircraft shape and the surface over which it is operating, together with the problems that intake and nozzle designs must solve.

SECTION 4. NOTEWORTHY AIRCRAFT TYPES offers a perspective on some of the more important VTOL aircraft of the past twenty-five years. It is possible that some of these designs and especially the designs of the engines developed for them may have something to offer anew now that interest in VTOL aircraft has been rekindled.

SECTION 5. THE PRESENT AND THE FUTURE records what is going on now (or at least what is public knowledge of what is going on now), and continues from the point where Section 1 left off.

It must be appreciated that in compiling a state of the art summary such as this it is necessary to stop the clock momentarily while the information is prepared. One use of this summary then is it can be consulted as a check list at any time after the preparation to see how much actual progress has been made.

A couple of times in its history VTOL has gained prominence in defence thinking, and it is possible that another such stage is upon us now.

SECTION 1. THE MILITARY CUSTOMER

It is twenty-five years since jet powered vertical takeoff was shown to be possible. During its brief history it has been hailed variously as "the greatest advance in aeronautical engineering since the Wright Brothers first launched their airplane" (T.P.Frost, Chief Test Pilot for Bristol Siddeley engines, 1963, Ref.1), as having possibly "the significance to modern aviation achieved by the gas turbine in the 1940's", (Vice Admiral Forrest Petersen, USN, Commander of Naval Air Systems Command 1977, Ref.2), which comparison echoed one voiced in 'Flight' magazine some twenty-two years previously (Ref.3). Yet in spite of the brilliance of its inception, the years of research that have been put into it, a NATO design requirement that specifically called for it, above all the sheer magic that a jet fighter aircraft can rise vertically from a clearing in a wood, fly off on a near-supersonic mission with a 5000 lb weapon load, come back to that clearing and do it all over again, the Jet V-STOL aircraft today is embodied in only two operational aircraft types, the Harrier and its cousins in the West, and the YAK-36 Forger in the East. Twenty-five years is a long time in aviation, twenty-five years took it from the Wright brothers to the first solo flight over the Atlantic, took the gas turbine from its first flight to being the only acceptable engine for naval aviation, yet twenty-five years of Jet V-STOL technology has very little to show for itself. Why is this?

The reason is not hard to discover. It is that until recently V-STOL has lacked a market. With the exception of the under-rated trick of being able to takeoff and land vertically, everything that a V-STOL aircraft can do can be done better and cheaper by a conventional aircraft of the same size. Competing aircraft have hitherto been judged on their own respective merits such as range, speed and payload, and not as part of a greater system in which support facilities, and particularly runways and flight decks must also be included in the cost account. In such a competition, the V-STOL aircraft must always come second because of the weight penalty incurred by its bigger power plant, and it is only when it is allowed to play the conventional aircraft on its home ground can it hope to win.

The same problem has, in its time, affected the helicopter. When compared against the conventional aircraft it was beaten on every count. It came out second best on every count, speed, range, simplicity, reliability, payload, cost, but when a role was found for it that exploited its unique talents, for operating from a small site or dock, for being able to dunk and recover a sonar transceiver, for being able to deliver people to and recover people from a site that otherwise would be inaccessible, it came into its own, not just as a curious sort of inferior aeroplane but as a functional flying machine in its own right.

So if a role can be found for a VTOL aircraft that only it can perform, so must it too set out on a process of development and realisation. The roles for a military jet V-STOL fighter/ground attack aircraft are now being written. As they develop it is likely that, if V-STOL did not now already exist, now is the time that a requirement would be drawn up to merit it.

The Role of the VTO Fighter/Ground Attack Aircraft Ashore

The first tentative step towards procuring an operational V-STOL fighter was made in 1959. At that time the Hawker Aircraft Company was developing plans for the P1127, a V-STOL aircraft designed to complement a vertical takeoff engine, the BS53 being designed by Bristol Siddeley The P1127 was a private venture, the BS53 was funded 75% by the Mutual Weapon Development Programme and 25% as a private venture by its manufacturers and there was no confirmed customer for either. However the attraction of the V-STOL idea led to the drafting of a NATO specification for such an aircraft to become the successor to the Fiat G91, and the Ministry of Supply lent its cautious support to placing contracts for the construction of two prototypes. V-STOL was now a potential weapon in the armoury. The P1127 demonstrated that it could fly during 1960, performing five hovering trials in November of that year, and full transitions the year after. International interest in the idea of VTOL aircraft increased to the degree that in 1962 an agreement was made to form a Tripartite Squadron of P1127s, now named the 'Kestrel', to find out what it could do as a potential operational aircraft, the countries concerned being the United Kingdom, the Federal Republic of Germany and the United States.

While Kestrel development was under way, an operational Research exercise was set up in 1963 with the object of its study being a limited war scenario East of Suez. The main subject to be investigated was the survivability of a close air support force, and one means of aiming to achieve this survivability was to disperse individual aircraft around at random, a mode of operation for which a V-STOL aircraft was particularly well suited. It was reasoned that an enemy would have to spend more effort in seeking out and destroying one such aircraft than he would in eliminating a whole airfield full of any other type, and the results of the O.R. study bore this out. V-STOL was shown to be the most cost-effective method of providing the close air support called for (Ref.4).

But by now the Kestrel was not the aircraft the Ministry of Defence had in mind. The draft NATO specification which had originally encouraged its construction had hardened into a requirement for a supersonic aircraft with a 250 mile radius of action carrying a 2000 lb store. This was not only beyond the Kestrel but its projected second-generation successor as well, the P1150. So this was in turn stretched to become the P1154, and both the Royal Air Force and the Royal Navy expected to get it. The P1154, which is described in more detail later in Section 4, was, of course, cancelled in 1965, but the need for some sort of V-STOL support fighter continued. Fortunately the Kestrel was already in existence and it was ordered to be developed for the Royal Air Force. In 1966 it was reborn as the Harrier.

In the summer of the following year the lesson of the 1963 Operations Research Study was demonstrated in earnest. In just two days of what became known as the Six Day War, the Israeli Air Force destroyed 393 Arab aircraft on the ground where they stood, and conventional airfields stood exposed in their vulnerability. An aggressor intent on eliminating an airforce on the ground knows where to look for it, and even if he failed to catch the aircraft in their nest he could effectively clip their wings by disabling their dispersal runways and taxiways. So the case for supporting the V-STOL ground support fighter apparently strengthened, the lesson was there to be learned, but it was not learned with either enthusiasm or application. Commenting on the war a year later, Robert Hotz, Editor of Aviation Week wrote:

> "Oddly enough, few of the high commands of the world's major Air Forces appear to be interested in this case history that is a watershed in the tactics of air war. Most of these major air force headquarters are still debating the now thoroughly academic question of whether there really is a military requirement for V-STOL aircraft instead of grappling with the urgent problems of how they can develop the strategy, tactics and logistics for the new type of air war V-STOL technology imposes.
>
> Military air power has grown to its present importance because it has been so quick to embrace and employ the galloping technology of Aerospace. It would indeed be ironic if it finally failed because it was unwilling to declare its independence from 1- and 2-mile ribbons of concrete." (Ref.5)

But Hotz could glean some comfort from the progress of the Harrier. In 1969 the Royal Air Force ordered 90 Harriers to be built, and the United States Marine Corps placed their first order for the Harrier MK50 in 1970, eventually to equip itself with no fewer than three front line squadrons and a training squadron.

The Harrier in the United States Marine Corps

The Harrier AV-8A is the close air support aircraft for the USMC, whose requirement was for an aircraft capable of covering an assault landing and then moving ashore with the landing force. Their enthusiasm for the aircraft is conveyed vividly by their Deputy Chief for Air quoted in International Defence Review (Ref.6): "We can bring the Marine trooper this air support as soon as he gets a little real estate ashore. When he is getting the hell kicked out of him, he wants that air support right now!"

The importance of rapid response is spelt out by the Deputy Chief of Staff for Aviation writing in Aircraft Engineering (Ref.7) where he says: "Most unplanned infantry type ground actions are generally decided in about 30 minutes. If you can't bring up your heavy fire-power within this period, you can have the best fire-power support aircraft in the world and still lose". This echoes an earlier quotation from Major General J.H.Miller in International Defence Review five years before (Ref.8): "Marine Corps experience is that fire-power at the proper time is at least as important as the weight delivered. It must arrive within a few minutes of the beginning of the engagement. An encounter of this size is usually decided within 20-25 minutes".

What emerges is this. An aircraft operating in close air support needs neither a great range nor a heavy payload, because instead of working from a secure airfield well inside allied lines and commuting to the battle area over a long range and taking a long time about it, it can be sited close to the front line. The USMC thinks in terms of placing its aircraft just out of enemy artillery range, about 20-25 miles from the enemy. Its time to target is of the order of 5 minutes and it engages from a posture of loitering on the ground, "where it don't cost a cent", rather than in the air. It is not the ordnance it can deliver in one sortie that counts, it is the weight it can deliver in one day.

The Harrier in the Royal Air Force

The Royal Air Force operates its Harriers in a similar manner to the US Marine Corps, and to a similar purpose, although their nearest approach to covering an armed landing has been the detachment operating in Belize, British Honduras. Their main deployment is in support of the British Army on the West German plain, and it is beyond doubt that should the line of battle there ever move at all, it will move very suddenly and very fast indeed, so speed of response is vital to successful defence.

They have developed extensive expertise in close air support for Army formations and also in the support and maintenance of their aircraft in forward sites where most impressive demonstrations of repeated high sortie rates have been made. This expertise will be available to be drawn on should the Royal Navy decide to proceed with plans for operating Harriers in small numbers from sub-capital ships in the future.

There is a worthwhile lesson to be learned from studying the success story of the Harrier. The P1127, although designed from the outset as an aircraft with a military future rather than as a pure research aircraft, was not intended to fill any particular vacant role, and when it grew up to become the Harrier it did so in the shadow of the more attractive P1154. Its only qualification to fill the breach when the P1154 was cancelled was that it was there as a tangible real aircraft, ready to be built on, not just as a plan ready to be redrafted, and from this ill-suited prototype there has grown an outstandingly successful aircraft, and one with potential still to be developed. This example should be remembered when we get involved in discussions and deliberations about whether or not to put the Sea Harrier in a small ship. Rather than seek a perfect role and requirement and follow that with preparation of a perfect solution, we should just go ahead and do it, and let the improvements follow from that solid fact of achievement.

The Role of the VTO Fighter/Ground Attack Aircraft at Sea

Before considering what roles the Sea Harrier and its possible successors will play in the Royal Navy it will be worthwhile to set the scene by considering the possible place of VTOL aircraft in the fleets competing for the prize of the largest global influence, the navies of the United States and the Union of Soviet Socialist Republics.

The United States Navy

The United States Navy came out of World War II with the most powerful fleet ever created, and its fighting unit was the Carrier Task Force. Generation by generation carriers got bigger and bigger, and the justification for this was that, for peacetime operations at least, a big ship could be shown to be more cost effective, ton-for-ton, than two lesser ships half its size. But there comes a stage in growth where, cost effectiveness notwithstanding, the cost of the next capital ship is so vast that it is time to call a halt. To have 2 billion dollars and 6000 men involved in one super-carrier like the USS 'Nimitz' must give rise to feelings of unease of having too many eggs in one basket. A 2 billion dollar basket, while being a superb prize for an enemy, is also a very attractive prize for a political party to cancel, and in a climate of decreasing defence expenditure, the USN are understandably eager to find some alternative route along which they can continue to proceed with sea power expansion without pricing themselves out of the market by incurring financial expansion to match.

Currently they can operate aircraft in the conventional manner from about fifteen decks; if they were to develop aircraft with the same offensive/defensive capability and a VTOL ability as well, this number would expand to 250-300 (Ref.9), so the attraction of VSTOL is obvious. The USMC has a splendid record of success with its AV-8A Harriers, and development of a V-STOL element in Naval Aviation could well be accelerated in its slipstream.

In the early 1970s the US Navy began to consider the idea of a Sea Control Ship for shipping protection in areas of reduced air threat. This bargain carrier was to weigh about 11,000 tons, carry about six Harriers and nine or ten anti-submarine helicopters and cost about $100,000,000, about one-tenth the then cost of a super carrier. The concept was exercised for a spell in the USS 'Guam', and then it got turned down by Congress when considering Defence Appropriations for Fiscal Year 1975 on the grounds that it would be too small to have any effect. The next plan was to consider a V-STOL carrier (CVV) of about 30,000 tons displacement, carrying about fifty aircraft and still equipped with catapults and arrester gear for the benefit of aircraft such as the S3A Viking. Its high performance aircraft would be the Rockwell XFV-12A supersonic fighter.

These mild flirtations with individual ship designs were eclipsed when in 1977 the United States Navy declared its intention to investigate whether V-STOL offered the potential to re-equip its seagoing aircraft inventory completely by the end of the century. Naval Air Systems Command called for design studies for three classes of V-STOL aircraft, unimaginatively termed V-STOL A, B and C.

V-STOL A described an auxiliary aircraft for AEW, Anti-Submarine Carrier on Board Delivery, Search and Rescue and carriage for assault troops. It was to be able to fit in the hangar of a DD-963 destroyer, and if successful would supersede the Viking, Tracker and Hawkeye in 1992. V-STOL B described a supersonic fighter/ground attack aircraft to replace the F-14 in 1994, the A-6 a year later, and even the F-18 by the first year of the 21st century, while V-STOL C would be a replacement for the LAMPS helicopter.

At the same time the USN expressed an interest in operating VTOL aircraft from small "non-commissioned" ships. If all these plans were to succeed, then in the next twenty years conventional naval aviation with big decks, catapults and arrester gear could become as out-dated as the seaplane-and-crane era. Current developments are discussed in Section 5.

The Soviet Navy

Ever since the end of World War II the threat posed by the Navy of the USSR has been that of its fleet of ocean-going submarines. The rest of its Navy, though admittedly possessed of great striking power, was assumed to be tasked with extended coastal defence, seldom needing to venture beyond the umbrella provided by the fleet of long-range shore-based maritime support and reconnaissance aircraft. There was little sign of any exercise of that traditional role of a national navy - showing the flag as a continuing reminder of its presence coupled with an assurance of goodwill.

The initial threat the Soviet Navy set out to counter was that posed by the strike capability of the task forces of the Western Fleet. They must be kept out of striking range on the Russian mainland. In time, however, that threat altered as that attack capability went underwater and developed a worldwide inter-continental capability. So whereas the challenge to the Soviet Naval planners had once been the neutralisation of the Carrier force, it now became the emasculation of the Polaris and Poseidon carrying submarines. They still believed that the best anti-submarine weapon was another submarine, and also, at the same time their fleet advanced from being an arm of the land forces and took on a global task of its own. They began to flex their muscles around the oceans of the world. Their roles were now threefold; to hunt submarines (i.e. anti-submarine), to defend their own submarines (i.e. anti-anti-submarine) and to put on a show of strength wherever their vast merchant fleet was seen to ply its trade (i.e. to show the flag).

The first Russian helicopter carriers, the Moscow and the Lenin were both well equipped with anti-submarine helicopters. When their first through deck carrier, the Kiev, appeared in 1976, the first of the 41,000 ton Kuril class, she was seen to be carrying the expected complement of anti-submarine helicopters and, in addition, a squadron of new VTOL fighter aircraft. These newcomers, designated YAK-36, code name Forger-A for the fighter and Forger-B for the two seat trainer version, are estimated to have a similar performance to the earlier Harrier, and so are not supersonic. One obvious role they could fill would be that of keeping anti-submarine aircraft, both rotary-wing and fixed-wing, at bay.

Two more ships of this class are in existence, the Minsk, already in commission, and the Xharkhov, still fitting out. The Soviet Navy, in choosing to equip itself with aircraft carriers has chosen to miss out a stage in the evolution of naval aviation altogether by doing without catapults and arrester gear, and has started off its excursions into the operation of fixed-wing aircraft at sea with an outfit of VTOL aircraft. Evidently their Navy, in seeking to expand its influence all round the world has a role for them and their successors. Additionally, should the Soviets advance to the production of a full-scale conventional aircraft carrier this could only indicate a determination to aim for total sea supremacy, meeting the US Navy head-on if necessary. Progress is being made in this direction (Ref.10).

The Royal Navy

The manufacturers of the P1127 wasted no time in demonstrating that the ability of their aircraft to operate from a small platform made it an ideal type to become a Naval aircraft and, in 1963, less than two years after its first airborne transitions from hover to forward flight and back to the hover, the prototype carried out a series of successful and incident-free trials in HMS Ark Royal at sea. During the following years the type was exercised from a variety of ships belonging to a variety of navies, and in 1971, Harriers of No.1 Squadron RAF embarked for a period in HMS Ark Royal to show that they could operate successfully as part of a carrier air group in harmony with Ark's Buccaneers, Gannets and Phantoms. While, again, the Harrier at sea could not do anything that could not be done better by the Services' own aircraft specifically procured for the job, this had no validity as an excuse for apathy towards V-STOL as it had done in other Services of other nations, because as far as the Royal Navy was concerned, by the end of 1978 the competition would be over, the Service's own aircraft would no longer be available to it, the discussion would be closed.

This had of course been foreseen since as long ago as 1965 when the Ark Royal's replacement carrier was cancelled, and during the twelve years remaining life of Ark Royal herself, the Navy had plenty of time to consider the options open to it which were either:

(1) To abandon fixed-wing aviation at sea altogether

or

(2) To continue fixed-wing aviation with whatever V-STOL had to offer.

Just as the RAF had only one aircraft type in being to choose from when insisting on V-STOL in 1965, so the descendant of that same type was all that was available to the Navy all those years later. So in 1974 the design of the Harrier FGR3 began to be adapted to become the Sea Harrier. How to make the most of it is the object of this study.

There is inevitably a large hiatus between what the Navy would like the Sea Harrier to do and what it is actually able to do. If the threat to British shipping is the 'Backfire' bomber armed with 120 mile range Mach 3 Kingfish AS6 missiles there is not much the Sea Harrier can do about it, but for slower more likely adversaries, for reconnaissance, for reaction against armed surface vessels, the Sea Harrier has much to offer.

While there are doubtless many studies in existence at a high level of classification concerning details of what the Sea Harrier is expected to do, none of these can be tried out until we get the aircraft to sea. The tri-national evaluation team which formed around the Kestrel in 1965 was set up to establish a squadron first and see what it could do second. The same attitude ought to guide the installation of Sea Harriers in units of the Fleet.

SUMMING UP

The main points to emerge so far are these:

- The VTOL fighter is recognised as a practicable weapon but has not been able to match the conventional fighter as long as runways and flight decks remain available.

- So far little practical development has been undertaken with the exception of the Harrier family, which was brought to maturity by the cancellation of the P1154, and the YAK-36.

- However, if runways and flight decks are to be denied the operator, either by their vulnerability to enemy action or on economic grounds, then the VTOL aircraft is worth looking at again.

Three major Navies are appraising V-STOL aircraft at present, each with a different purpose:

The United States Navy is looking towards V-STOL as an alternative means of expanding its current role. It will choose between V-STOL and CTOL only on the grounds of which one offers the better value for the same service.

The Soviet Navy has started off with V-STOL for its first ever venture into embarked fixed wing operations. It is developing along a steeper line than the US Navy, and having bypassed CTOL altogether, is likely to be well on the way to producing advanced VTOL aircraft.

The Royal Navy now has no alternative to V-STOL if it is to stay in the game of operating fighters at sea at all. It therefore has the strongest incentive to make a success of it.

SECTION 2. POWER FOR V-STOL

There are two simple engineering requirements which will lead to a successful vertical take-off power plant design. They are:

(1) The thrust developed by the power plant must be greater than the weight of the aircraft by a comfortable margin.

(2) This thrust should be achieved with an intake efficiency of well over 95%.

While these requirements appear simple to the point of naivete, the problem of satisfying them both simultaneously is one that has exercised engine and aircraft designers on both sides of the Atlantic for nearly thirty years, with very little operational hardware to show for their efforts.

Engine Thrust

As may be seen from Fig.1 the thrust required to give an aircraft a most impressive performance need not be greater than about 50% of its weight at take-off. From the same graph it can be seen that as the aircraft increase in performance the proportion of All-Up-Weight represented by the engine increases also. So if an engine is required that will produce a thrust equal to or greater than the weight of the aircraft, which is the first requirement for Jet VTOL, that engine is going to be disproportionately heavy for the aircraft it is going to propel. So the first problem to assail the designer of a VTOL aircraft is how to deal with this weight penalty. Once the aircraft is safely airborne and supported by the lift of its wings, the main task of the engine is done because an engine of half its size would be adequate to give the aircraft the performance demanded of it for the rest of the flight, and the weight to be supported when landing will be only about half that at takeoff. So the balance of the engine weight, together with its volume and draggy bulk, form a non-contributing burden for the aircraft for its entire flight. To illustrate with an example, the VTO version of the Mirage III, designed and flown as a competitor to the P1154, suffered a weight penalty of 17% compared with its conventional opposite number in the Mirage III range.

However, the story is not as depressing as it might appear from this introduction. Once the problem had been recognised as one of producing extra thrust for only a brief period, methods of generating this for very little extra weight cost were devised, and the burden associated with having the aircraft over-engined was lightened considerably.

Efficiency

An aircraft is lifted and propelled by the displacement of air from above and ahead of it to below and behind it. The amount of lift generated is proportional to the rate of change of momentum of that air displaced, i.e.:

$$\text{Lift} \propto (\text{Air Mass Flow}) \times (\text{Speed})$$

The power required to bring this about is the product of the Force (i.e. Lift) and the Speed, so:

$$\text{Power required} \propto (\text{Air Mass Flow}) \times (\text{Speed})^2$$

Therefore, because of this $(\text{Speed})^2$ term it will take less power to produce a given amount of lift if it is a product of a high mass flow rate and a low speed than vice versa. So unfortunately, a small engine delivering air at a very high speed is a woefully inefficient lift producer.

The possible means of giving lift to a flying body may be listed in increasing order of inefficiency as follows:

Balloon : (V-large displacement; very slow speed)

Fixed Wing : (Large displacement; air at aircraft speed)

Rotating wing : (Smaller wing area displacing air faster)

Propeller : (Smaller still and faster still)

Pure Jet Engine : (Very small flow; very high speed)

To illustrate with another example, a Harrier hovering at 15000 lbs will be consuming fuel about 12 times faster than a Wessex helicopter hovering at the same weight. Clearly if the sole criterion on which to base a means of propelling a VTO aircraft were engine efficiency, then the Jet engine would never be considered. Fortunately it is not simply the rate of fuel burn at takeoff which concerns the designer, it is how long it is being burned for, because this decides the weight of fuel used. If an aircraft is required to hover for only a very brief period then a small high-powered but inefficient jet engine might be an acceptable method of producing the extra lift called for.

Pure Jet V-TOL

Pure Jet VTOL became possible only when the jet engine had reached the stage where there was enough of a difference between its static thrust and its own weight plus fuel to accommodate the weight of some sort of airframe. This was first shown to have been reached in 1953 when the Rolls-Royce Flying Bedstead performed its first tethered hover, and more convincingly on August 3rd 1954 when it achieved its first free flight. The margin between the thrust of its two Rolls-Royce Nenes and its weight was only sufficient to permit it to carry enough fuel for an endurance of 9½ minutes.

(As a point of interest, the Flying Bedstead was not the first flying machine to rise on its engine power alone. This notable first was the prerogative of the Convair XFY-1, powered by a 5850 hp Allison engine driging contra-rotating propellers producing 18500 lb thrust to lift an aircraft weighing 15000 lb. It beat the Flying Bedstead by one day, and demonstrated that jet power could be more readily used if geared through propellors to increase mass-flow and reduce air speed).

In 1954 too the Bell Aircraft Company flew their "answer to the British flying bedstead" (**Fig**. 2). This machine was given power for lift by two Fairchild J44 engines each producing 1000 lb static thrust, and able to operate vertically for lift or to tilt to a horizontal attitude for forward flight. Control in the hover came from reactive puffer-jets fed from a Palouste gas generator mounted above the fuselage. The aircraft was able to take off vertically only by virtue of the extreme austerity of its construction. Its wing was that of a light aircraft, its fuselage was from a glider and its landing skids were from a helicopter. Its engines weighed 310 lb apiece, so their thrust of 1000 lb left a margin of 2 x (1000 - 310)lb = 1380 lb into which the entire structure, including its pilot and fuel, had to be fitted. With the specific fuel consumption of each engine being 1.65 lb/lb/hr it can be deduced that the endurance of this aircraft in the hover must have been very small indeed.

The lesson of these early attempts at jet-lift vertical takeoff was that the gap between what an engine developed and what it weighed would have to be increased enormously if a worthwhile aircraft was to be fitted in. And for small margins the effect of developing anything less than 100% efficiency would be at its most marked. If the margin for fuel, say, was only 5% then a loss of over 1% in thrust would offset one-fifth of the fuel capacity and hence one-fifth of the range/endurance, and 1% can easily be accounted for by small temperature variations at the intake, fouling on the compressor or all manner of small inperfections. The designer in the early days was caught in a trap from which an enormous development in engine technology would be needed to free him. (Fig.3).

Even when this problem was solved, that of the mis-match between the thrust at takeoff and the maximum possible thrust demanded at high speed still remained. It might be thought that this extra thrust will be required again to achieve maximum speed, but even then supply and demand are well out of balance. The American F4 Phantom will serve to demonstrate this. With a maximum takeoff weight of 54,000lb and a maximum takeoff thrust of 34000 lb it reaches a creditable Mach 2+. This means that it can achieve its required performance with a takeoff thrust/weight ratio of 70%, i.e. on 30% less thrust than its VTO counterpart would have available. The inference is that the VTO counterpart if built, would be able to match its full power requirements for maximum speed and for vertical takeoff only being inefficient somewhere along the spectrum and would therefore be bound to be outclassed by the Phantom itself.

A Design Example

Consider a requirement for a Ground Attack V-STOL fighter of medium performance comparable with its peers in the late 1950s/early 1960s. Their maximum takeoff weight is about 12000 lb and their maximum thrust/weight ratio is about 40%. The designer at the time would look for a propulsion system satisfying one of the following descriptions:

(1) The engine or engines could be chosen to develop something in excess of 12000 lb thrust and the aircraft configured to takeoff pointing upwards like a rocket. In this case the engines would weigh about 3000 lb and 7200 lb of its thrust would be surplus to requirements after takeoff. In addition the aircraft would need a conventional undercarriage as well as a tail undercarriage, (unless it was intended to land and taxi in the same attitude in which it takes off), which means more weight.

(2) An engine of the same output could be used and takeoff could be flat. A single engine would be simplest. Producing 12000 lb, it would weigh about 3000 lb and would have to be able to point its jets downwards as well as backwards. It is going to produce more power than is required for maximum cruise so it is going to be inefficient and so need more fuel for long range than is strictly necessary. Its performance when lifting will be improved with increasing mass flow, so a degree of bypass is desirable. This means it is unlikely to be supersonic.

(3) A straight jet engine of 5000 lb thrust could be used for cruise, while lift could come from a clutch of vertically-orientated high thrust/weight engines. It is easier to get a high thrust/weight ratio out of a small engine than a big one, so a number will be required, say eight producing 1500 lb apiece, and weighing 250 lb each.

(4) If three of these lift engines could be rotated in their mountings through 90^o then they could produce thrust for forward flight as well as for lift. But as lift engines it was acceptable that they could be inefficient. This allowance might no longer apply if they are to be in use for

the whole flight. So either a more elaborate engine must be developed, or more fuel must be carried, and, if the latter, then there goes the saving in weight achieved by dispensing with the cruise engine in Case (3).

(5) The cruise engine in Case (3) could also be diverted to produce lift; the balance could be met by five lift engines.

(6) The lift/cruise engine in Case (5) could be capable of producing extra thrust at takeoff, either by afterburning or by producing static thrust more efficiently than by pure jets, e.g. by driving a fan. Both these stratagems would add weight of the same order as a lift engine, and the balance of thrust could be made up by further lift engines.

In all these cases of mixing power plants the best solution can only be established when all the facts and figures are known, especially not until the mission is known because evidently it is crucial to the optimizing calculation to know just how much fuel is likely to be required for each phase. As a spokesman for the NASA research centre at Langley Air Force Base observed, writing in the Journal of Aircraft in 1971 (Ref.1):

> "The lack of definition of a mission has been one of the difficulties which has prevented focussing on a particular type of V-STOL aircraft and pursuing its development into a commercially feasible vehicle".

But before getting involved in the endless arguments and discussions about which is the best mixture of engine types to power a given V-STOL aircraft, let us consider for a while the new engine types that V-STOL has called into being, namely the Lightweight Lift engine and the bypass engine with vectored thrust.

The Lightweight Lift Engine

At the time of the debut of the Flying Bedstead, Rolls-Royce were already looking at the design of an ultra light gas turbine engine and in 1955 they produced the 'SOAR' as their first example, felicitously named after a river in Warwickshire. It weighed only 270 lb, was only 40cm in diameter yet it produced 1820 lb static thrust. The SOAR only ever flew as a booster engine but it paved the way for the leader of a range of lightweight engines intended particularly for use in V-STOL aircraft, the RB 108.

This delivered 2010 lb from a dry weight of 269 lb, leaving some 1700 lb to spare. A pack of four RB 108s provided the lift for the Short SC1 VTOL research aircraft, while a fifth was aligned fore-and-aft for propulsion (Fig.4).

The RB 108 was the first of a new class of engine whose design for construction, performance, economics and reliability had aims greatly different from those relevant to propulsion engines. They were meant to be started after the main propulsion engine was running, maybe not until the takeoff point on the airfield had been reached, they would get the aircraft off the ground, and once speed had built up enough to permit wing-borne flight to proceed they would be shut down and forgotten about until they were relit preparatory to landing when they would be given another brief spurt of application. So they were built with a slim cross section so the resulting low polar moment of inertia would permit an exceptionally rapid throttle response, they drove no auxiliaries and needed no long overhaul life, they were simply fixed intake axial flow engines and, most important of all, they were very light.

The RB 108 was proved in the SC1 aircraft and had its biggest application in the Dassault Balzac V001. This was a reworked Mirage prototype, produced as a stepping stone on the way to a V-STOL Mirage III. The Balzac was lifted by a batch of eight RB 108s disposed in four pairs about the aircraft's centre of gravity and inclined slightly forwards so they could contribute to forward acceleration.

The RB 108 was succeeded by the 2750 lb output RB 145. This was later to be the first lift engine to achieve supersonic flight, and also the first to accomplish a takeoff in reheat, both occasions in the EWR VJ-101C-X2 which had two mounted in a swivelling pod at each wing tip and a further pair in the fuselage. (Fig.5).

Next came the RB 162. This produced twice the thrust of the RB 108, yet, thanks to the extensive use of composites in its construction it still weighed only 275 lb, offering a thrust/weight ratio of 16:1. In use it was started by direct impingement of air from the propulsion engine onto its turbine, and this action also initiated the delivery of a squirt of lubricating oil to each of its only two bearings, more than enough to protect them during the brief few minutes they would be running during the takeoff or landing cycle. In their day, in the early 1960s, these lift engines were specified for a most impressive array of V-STOL aircraft, Civil and Military alike - Breuget BR 1110, British Aircraft Corporation BAC 584, Dassault Mirage III V, de Havilland DH 129, Dornier DO 31, Fiat G 95/6, Focke Wulf FW 262 and FW 1262, EWR-Sud VJ 101D, Lockheed-Short CL 704 and many others, few of which ever flew, none of which ever got into service.

The RB 162 is, however, still going strong. As the RB-162-81 it serves as an in-flight booster engine for the Trident IIIB. Nor has development ceased. In co-operation with Allison of General Motors, in 1966 Rolls-Royce embarked on a third generation lift jet and this, the XJ 99, first ran in 1969, developing a thrust of 9000 lb from a weight of only 450 lb. A year later came mention of a civil lift fan project, the RB 202 developing 10,000 lb+. The XJ 99 is apparently still available; all it requires is an aircraft to lift.

The Lift/Cruise Engine

Use of a single jet engine to raise vertically and propel an aircraft was successfully demonstrated at Edwards Air Force Base on May 28, 1956, when the Ryan X-13 made its first tail sitting flight. It was powered by a single Rolls-Royce Avon RA 14 delivering 10,000 lb thrust, and the overall thrust/weight ratio of the aircraft was 1.3:1. Four years later the research of the project was completed, both X-13 prototypes were honourably retired to Museums and no further use of the vertical takeoff was made, at least not for twenty years.

Vertical attitude takeoff has some attraction, especially for embarked use where the gantries and moorings required can be installed more readily than a long landing surface and the aircraft need not be moved far away from its handling rigs. But in general, horizontal attitude vertical takeoff and landing is more attractive, the pilot can see where he is going and the option of performing an overload takeoff in STOL configuration remains open.

So the requirement exists for the engine jet efflux to be capable of being diverted downwards as well as backwards. This diversion must be carried out with clinical efficiency as every pound of thrust lost through ducting and pipework means a pound less in disposable load.

Thrust vectoring is not new, indeed it was tried as a method of facilitating the control of Airships at the time of the Great War, but its first study in the current era was undertaken by Westlands in 1955 when they were given a contract by the Ministry of Supply to carry out trials on a Gloster Meteor whose Nene engines could direct their exhaust downwards in flight (Ref.2). The trials showed it was possible to effect a reduction of 20% in the safe flying speed of the aircraft, but, curiously, Westlands were "forbidden" to investigate what happened at lower speeds.

The first engine designed to operate with vectored thrust was the Bristol RB 53. This engine developed from an idea by a French engineer, one Marcel Wibault, for a version of the Bristol Orion engine, a first cousin of the Proteus, driving a pair of centrifugal compressors mounted one either side of it like a pair of front wheels, and exhausting through a straight jet pipe. The compressors could be rotated so as to exhaust horizontally or vertically. M.Wibault's proposal was submitted to staff on the MWDP (Mutual Weapons Development Program), who brought it to the attention of Bristol Siddeley Engines. Bristols were attracted by the idea and developed it further by substituting an Orpheus for the Orion, by installing an Olympus compressor in place of the centrifugal compressors and by splitting the straight through jet pipe into two by inverting a bifurcated splitter-pipe developed from the jet pipe of the Sea Hawk. The shape of the Pegasus had arrived.

The new engine began development as the BS 53 from which came the Pegasus (Fig.6). It was funded 75% by the MWDP and 25% by Bristols themselves as a private venture, and it made its debut in the P1127 in 1960. At that time it developed 13500 lb to lift an aircraft whose empty weight was 12000 lb. Development has brought it up to 21500 lb in its present form, with 24500 lb planned for the next step. Although some other vectored thrust engines have been schemed, including the R R Medway for the HS 681 tactical transport and the twin-spey installation in the Naval version of the P1154, the only one other than the Pegasus to have flown in the West is the Rolls-Royce/MAN 193 in the VFW VAK-191-B.

The Variable Output Engine

An ideal thrust system for VTOL is one which can be matched to the power requirements for economical cruise and yet deliver extra lift power for short periods at minimal extra cost, weight and complexity. Certainly the penalty for this laudable flexibility should be less than that incurred by installing a separate lift engine for the same purpose. There are three different systems for thrust augmentation that fit this requirement. They are:

Afterburning
Fan Lift and
Augmentor and ejector nozzles.

Afterburning

The idea of injecting extra fuel to burn in the exhaust streams of a jet engine and so obtain extra thrust, albeit at a price is well known and widely applied. The only engines to which reheat has been applied in practice in the vertical takeoff mode are the RB 145 in the VJ-101-C-X2 and the BS 100, developed for the P1154. The thrust developed by the BS 100 is 30,000 lb giving it a thrust/weight ratio of 13:1 in afterburner compared with 6:1 for the 'dry' Pegasus from which it was developed.

The particular form in which reheat was applied to the Pegasus derivative is called Plenum Chamber Burning (PCB). In order to boost the takeoff thrust of the Pegasus it would have been possible to apply reheat to both sets of nozzles. When considering the design, Bristol Siddeley decided against this on the grounds that to have three combustion systems in the one engine might prove to be unmanageable, and they rejected, too, the ideas of installing reheat in the hot end alone by means of replacing the divided jet pipe by a straight-through system with a deflector because of the centre of gravity problems they saw would result. What remained was to apply burn at the cold end alone. Here there was scope for considerable thrust magnification because of the relatively low temperature at the LP outlet. In the Pegasus the ducts leading the bypass air from the LP compressor to the cold nozzles had the effect of distorting the symmetry of the circumferential static delivery pressure distribution, leading to cyclic blade vibration on the fan. This problem was cured by reprofiling the exit duct to include a collecting chamber to dampen down the waves causing this pressure cycling effect. The collecting chamber, or Plenum Chamber was the site where the afterburning nozzles were positioned.

Just like the XJ 99 advanced lift engine, the BS 100 advanced vectored thrust engine still awaits a practical application.

Fan Lift

A high jet velocity is a very inefficient producer of thrust when the aircraft is standing still. What is required is a means of converting its energy stream of high jet velocity and low mass flow into one with a low jet velocity and a high mass flow. One method of achieving this is to use the jet to drive a fan, which has the same result in effect as introducing a bypass stage into the engine.

The fan system was first used in the Ryan XV-5A which was developed under contract for the United States Air Force, and flew for the first time on 25 May 1964.

In this system the jet efflux of the propulsion engines is diverted in the hover to drive two horizontally disposed fans, one in each wing, plus another, smaller, one in the nose, the driving method being by impingement on impulse turbine blades around the rim. In the Ryan XV-5A the wing fans were each of 5'2" diameter, and powered by two cruise engines each of 2660 lb static thrust they were able to bestow lift on an aircraft where all-up-weight for vertical takeoff was 12,300 lb.

Once the aircraft was airborne on wing-borne flight, semi-circular doors over the fan inlets were closed, the jet efflux was directed backwards and the XV-5A flew as a conventional aircraft, with a speed in excess of 500 knots. The Ryan aircraft is an example of lift fans being driven by gas-coupling. Mechanical coupling is also, of course, an alternative approach to the same solution. It calls for a fairly complex installation of gear trains and clutches (to cope with the engine failure cases), and is suited to V-STOL transport aircraft. It has been used in the CL 84, XC-142 and Breguet 941 with success, and in such installations it can be arranged for the fans to be all able to pivot about a lateral axis and used for forward flight.

Augmentor/Ejector Nozzles

Another means of getting a gas stream with a high velocity and a low mass flow to retain its energy but exchange its characteristics is by using the high velocity jet as the core of a jet pump to entrain ambient air causing the whole mixture to gain extra mass and also slow down. The total momentum remains the same but the proportions of its constituents are more acceptable for static hovering flight.

An aircraft to lift entirely by the efforts of its jet efflux being augmented in this way was the Lockheed XV-4A Hummingbird. In vertical takeoff, the whole jet efflux from its two engines was reversed through 180° and ducted forwards into side-by-side longitudinal ejector ducts extending the length of the fuselage. It was then discharged downwards through rows of multiple nozzles into two ejector chambers. Above and below there were bomb-bay type doors that would be closed during horizontal flight. The exhaust pulled in air and boosted the thrust by a claimed 40%. Figures for the Hummingbird show that its total thrust was 6600 lb and its maximum weight for vertical takeoff was 7200 lb, so this represents a net improvement of at least 8%, and assuming a required 2% excess of thrust over weight for VTOL, a fairer figure on which to assess the improvement is nearer 15%. The XV-4A program was concluded in 1964 because "circumstances did not allow the continued development of ejector technology and improvements to the ducting which would have produced a flight-weight ejector system". The inference to be drawn is that thrust augmentations by ejector did not work as well as had been hoped.

What appears to have happened is that the theory is more complicated to put into practice than it first appears. Efficient mixing of two streams of air of different speeds is very difficult to achieve as the practical losses cancel out the theoretical gains, which should be up to 70% (Ref.3).

The principle of thrust augmentation in a wing is illustrated in Fig.7. In 1973 a further attempt was launched to put it in to practice when a contract was placed with Rockwell International to build two prototypes of an augmentor-wing aircraft for use as a V-STOL naval fighter capable of Mach 2+ and powered by a single Pratt and Whitney F401 engine (the engine of which two are in the F14B Tomcat). This aircraft, the XFV-12A, although scheduled to fly in 1976 had not yet achieved free flight by August 1979.

Remote Augmented Lift System (RALS)

A newcomer on the scene, and as yet unproven, is RALS. This supplies power to the front nozzle of the conceptual aircraft illustrated in Part 1 Fig.01, and is shown in block form in Fig.9. It is the brainchild of General Electric and uses a bypass ratio 0.7 fan engine with a variable cycle, capability including front and rear variable area bypass injectors, a variable area low pressure turbine and a double bypass split fan. The front block of the fan is oversized to provide additional airflow for V-STOL and transonic requirements. The engine has a partial afterburner for provision of additional thrust at certain forward flight conditions, but not for vertical takeoff or landing.

When RALS is in operation during vertical takeoff and landing, all bypass air from both engines is directed via common ducting to a forward location where it is augmented with a simple burner and expanded through a downwards exhausting nozzle. The burner temperature is normally 1370^{O}K, but can be varied over the range 516^{O}K - 2033^{O}K to provide a thrust change for pitch control. The nozzle has a vectoring capability of 30^{O} aft, 20^{O} forward and 15^{O} laterally.

The layout is comparable with a Pegasus, the cold nozzles extended right forward and equipped with a variable form of PCB. It is based on expected engine technology of fifteen years hence and it seems unlikely ever to be realised unless a decision is taken to proceed with the US Navy requirement for V-STOL B.

The Choice of Engine System and Layout for V-TOL

In the face of all the theories which can be applied to the selection of the ideal power plant mix for any desired theoretical VTOL aircraft, it is ironic to report that the only such aircraft to meet real success is the Harrier with its single dry, lift/cruise engine. Its mission profile has been based on its engine capability, (and not the other way round) and what has resulted has been very close to what would have been required. (It is possible that too much stress is given to the concept of the mission profile when specifying and designing an aircraft. Practical experience is that military aircraft are very rarely worked to the exact ranges and with the precise payloads they were designed for. The reality is that the Military gets an aircraft and then sets out to compile a repertoire of missions it is best for.)

Lift/Cruise Engine

A single vectored-thrust engine has some quite telling advantages over other installations. They include:

(1) The simplicity of a single engine installation, plumbing, control and instrumentation.

(2) Greater thrust available for acceleration and climb.

(3) All checks and ground runs can be carried out with the nozzles horizontal, thus avoiding ground erosion and debris and jet efflux ingestion.

(4) An optional short-takeoff can be schemed for overload conditions.

(5) The total thrust can easily be arranged to pass through the aircraft centre of gravity.

Its main disadvantage is that its cross-sectional area, and the size of its intakes in particular, militate against efficient supersonic flight.

Lift Engines

If lift engines have to be incorporated in the design being considered they have their secondary virtues such as

(1) They are cheap to supply

(2) They are simple, and therefore simple to maintain

(3) They have a small cross-section so they:

  (i) Allow slim aircraft to be built around them

  (ii) Have a small moment of inertia and are therefore very responsive to changing power demands

and their problems, including:

(1) Non contributory weight in horizontal flight

(2) Need for extra intakes (with doors), and extra exhausts.

Lift Fan Systems

The subject of relating the best mixture of Vectored Thrust Lift/Cruise engines and Pure Lift engines for a given application has already been aired. The Lift Fan system, however, seems to have received less recognition than its due.

It can be employed in two ways. Either the whole lifting force can come from fans, two in the wing and one in the nose, as in the Ryan aircraft, or it can come mostly from a vectored thrust engine mounted aft in the aircraft with a fan in the nose providing a balancing force. This latter system is particularly attractive for a supersonic design where the bulk of a vectored-thrust engine is most unwelcome half-way along the fuselage, but may be acceptable further back.

A lift fan can augment the thrust of the engine by about 300%/400%. Thus if a one-to-one ratio is produced at takeoff, then the ratio in cruise will be about 1:4 which is in the required range for a high performance subsonic aircraft. If lower augmentation is used, with a bigger engine, the resulting values of thrust/weight ratio correspond with those appropriate to aircraft with high subsonic and supersonic performance.

With the fan installed in the wing, the depth of the wing is decided. If the design of the aircraft calls for a wing with a low thickness/chord ratio, then, with the thickness dictated by the presence of the fan, it follows that the chord of the wing will have to be large. Matching a high speed aircraft to a large chord necessitates a low aspect ratio, and this means a short, stiff wing in which the cutout for the fan can be tolerated. So it can be demonstrated, in a roundabout fashion, that a fan-in-wing aircraft is doubly suitable for high performance specifications.

The lift fan system has a lot to offer. Interest in it has been renewed in the USA in recent years (Ref.4) although no high performance designs have been published.

Safety

A further consideration to confront the designer when relating his power system from the vast range of choices open to him is the question of safety and survivability in the event of failure of one or more engines. Has his aircraft got enough power to get back?

The points for and against a single or a multiple engine installation in a conventional aircraft are well known. They range from the argument that a large engine will be more expensive to develop than a small one, so as its development costs have to be spread over a smaller buy of engines its cost per unit will be more expensive still, to Lindberg's observation that two engines are twice the trouble.

But the main argument, and one which usually wins the day for the supporters of the multi-engine side, is that the probability of two or more engines all failing is far less than that for one, and so, assuming of course that the aircraft can stay airborne on one engine, the survivability, sometimes called the integrity, of the twin or multi- is much higher. Figures lending more weight to the twin engine exponent appear in (Ref.5) which gives the attrition rate of single engined military aircraft to be two and a half times greater than that of their twin engined equivalents with similar values of wing loading and approach speed.

This is all very fine for conventional aircraft, but it is not so easy to read across from the same philosophy and apply it to those with a V-STOL capability. Preservation of safety in cruise flight presents no great problem. Straightforward cruise engines can be doubled up just as in a conventional aircraft. Lift/cruise engines are more difficult but possible at the cost of wide or long installations, because the engines themselves and their intakes are wide in cross-section for the cruise thrust required of them.

Safety in the hover presents a different problem altogether. For pure lightweight lift engines there will indeed be safety in numbers so long as their thrust lines are not too far apart, for the threat in hover comes not only from loss of lift but from loss of balance also. If only one or two pure lift engines are used, as in the YAK-36 Forger or the VAK-191-B, reassurance can be taken from the knowledge that the Mean Time between failure of a modern engine is very high, of the order of hundreds of hours, the time spent in the hover is very low, of the order of a few minutes so the risk of engine failure during any given hover is very remote.

For vectored-thrust engines the risk of loss of control brought about by failure of one of a pair of engines can be reduced substantially by arranging their jetpipes to feed into a common set of nozzles. This was the solution offered when the Royal Navy expressed its total reluctance to accept the P1154 with a single BS 100 engine. The BS 100 was replaced by a design using two Speys, side by side, each feeding into the pairs of nozzles fore and aft. Both the lift-fan and augmentor nozzle systems are suited to be fed by more than one engine. For instance, the Ryan XV-5A has two engines (2 x J75), and each engine produces half the thrust required to drive each of the three lift-fans, so that failure of one engine need not be disastrous, even when in the hover.

Summing-Up

Jet power to raise an aircraft vertically may be delivered by any of the following systems, used either singly or in combination:

(1) Straight Lift, as in the Ryan X-13 Vertijet. Some aircraft now, such as the F-16, have a Lift-Weight ratio greater than one, and theoretically they should be able to take off in a vertical attitude. All they need is an additional method of control for use while their speed builds up enough for their standard flying controls to become effective, plus a means of setting the aircraft upright before takeoff. A tail-sitting undercarriage would be suitable if it was intended to land in the same attitude, and this could be lighter than the usual design because the vertical and horizontal demands made on it would be less

exacting. Ground handling in this case would call for the use of special dollies or cradles, but, taken on the whole, now that power is available for truly vertical takeoff, the idea is a most attractive one, and one particularly suited for use aboard ships where the requirement to travel a long way on the surface does not arise.

(2) Lift Engines, as in the Dassault Balzac. A specialist range of pure lift engines was developed by Rolls-Royce expressly for this purpose. They are simple, outstandingly reliable because of that simplicity and are exceedingly productive for the weight penalty they impose on the aircraft in cruise. The Rolls-Royce Allison XJ-99 engine weighs 450 lb and produces a thrust of 9000 lb. Assuming an installation weight equal to the weight of the engine, and an s.f.c. as high as 1 lb/lb/hr, an installation of 2 x XJ 99s with fuel for three minutes hover would weigh 2700 lb and deliver a net 15000 lb of lift.

(3) Lift/Cruise (Vectored Thrust) engines, as in the Harrier family. This is a well proven system. Its mid-position installation and its large intakes make it unsuitable on its own for supersonic aircraft, but this drawback could be avoided if a lift engine or lift-fan were installed at the front of the aircraft, allowing the main engine to be resited at the back. Its excess of thrust for cruising flight has been turned from a handicap into a positive virtue by being made use of for VIFF'ing (Vectoring in Forward Flight), now a practical tactical evasive manoeuvre.

(4) Fan Lift as in the XV-5A. This is an attractive and extremely versatile system. It is in course of being employed in some experimental low-subsonic multi-engined convert-planes in which the driven fans may tilt to produce forward drive as well as lift, but it should be worth looking at anew for aircraft of higher performance. The downwash from a fan-in-wing installation will be much slower, cooler and quieter than from a jet-lift engine.

(5) Augmentor/Ejector Nozzles (Augmentor wing) as in the original XV-4A Hummingbird where the lift was generated from the fuselage (thus denying the aircraft most of its internal carrying capacity), and in the projected XFV-12A, where long ejector nozzles run the span of the wing and canard foreplane. Should the XFV-12A eventually succeed, and actually develop the theoretical augmentation of X1.7, it will be an attractive system. It has no rotating parts, and, like the fan-in-wing XV-5A its footprint is cool.

(6) Remote Augmented Lift System. A RALS installation offers an alternative to a front Lift engine or Lift Fan in an aircraft where consideration of area ruling require the engines to be located well aft and so some form of frontal lift is necessary for balance in the hover. The

RALS ducting takes up a lot of fuselage space compared with a pure lift engine (see Fig.01), and the system suffers from the inelegance that air which has travelled all the way down from the intakes to the compressor face is required to be reversed and sent all the way back again. Aside from that, the system appears to have a lot in common with the PCB variant of the Pegasus, and as such, it shares many of its advantages.

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FIGURES

SECTION 2

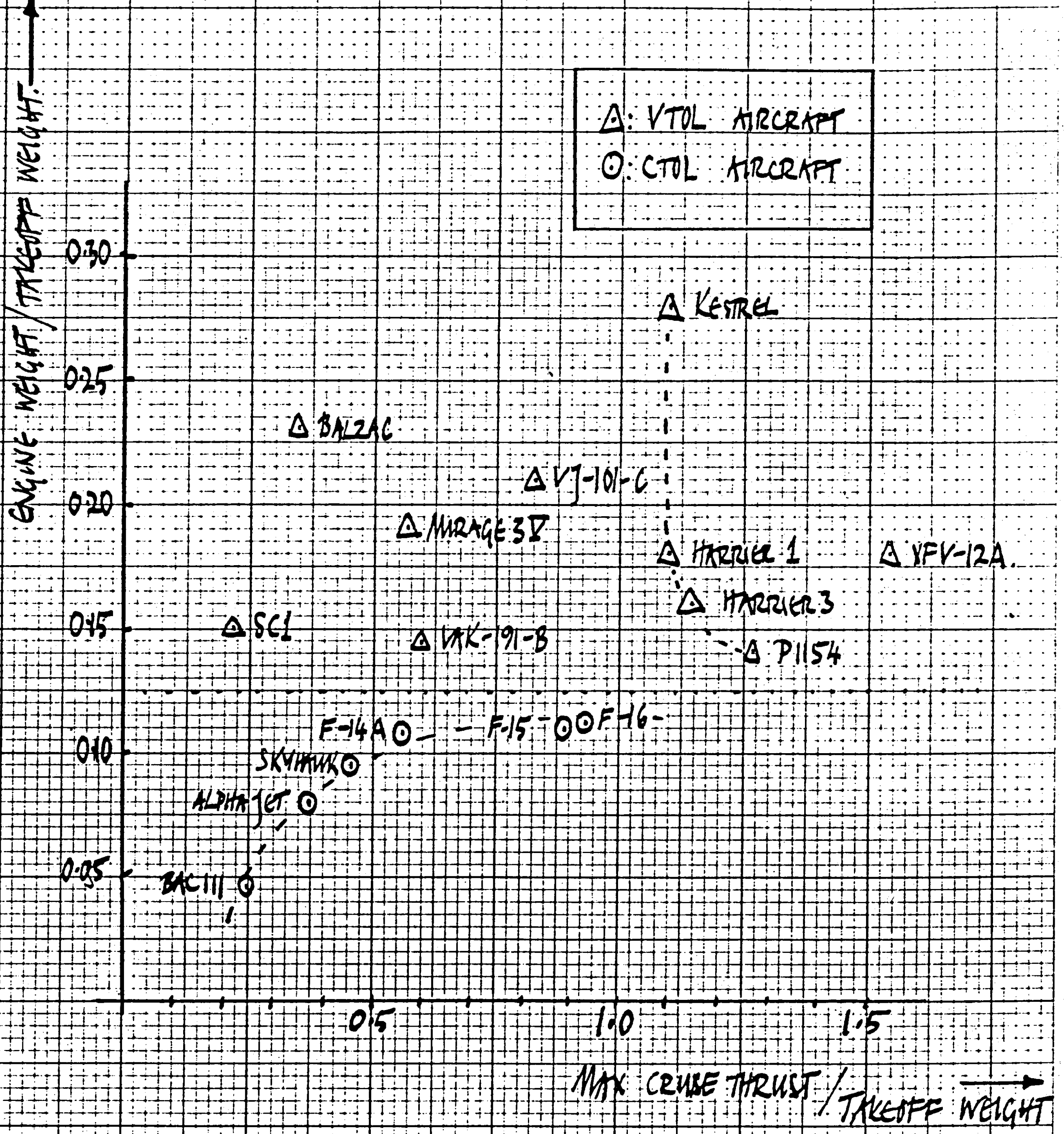


Fig 1: Aircraft Thrust/Weight vs Engine/Weight

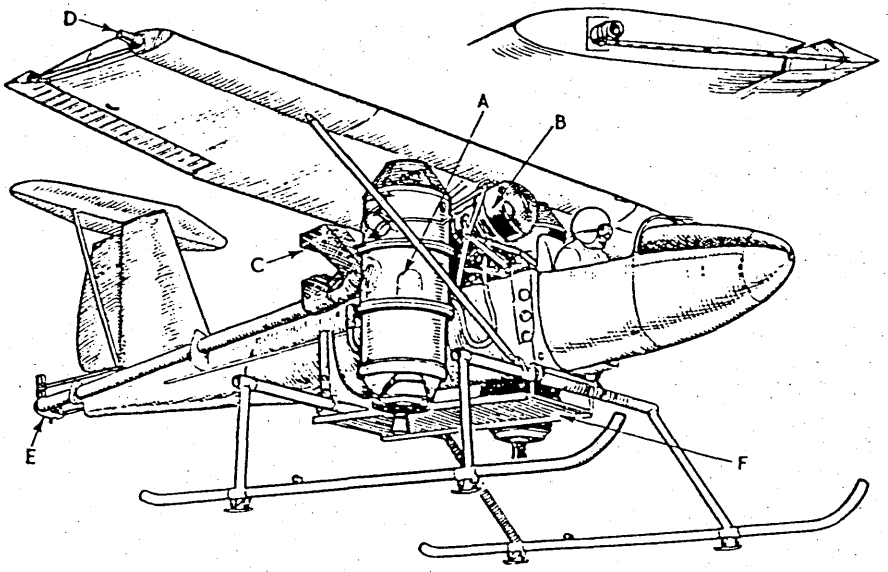


Fig 2: The Bell "Vertical Riser"

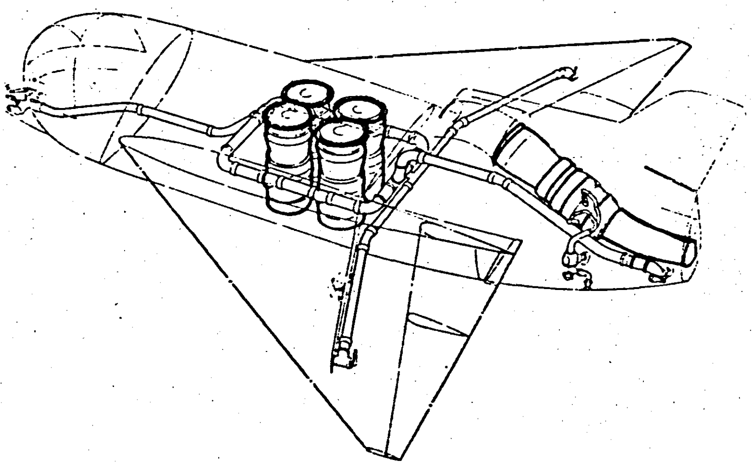


Fig 4: Engine Layout in Short SC1

E.R.

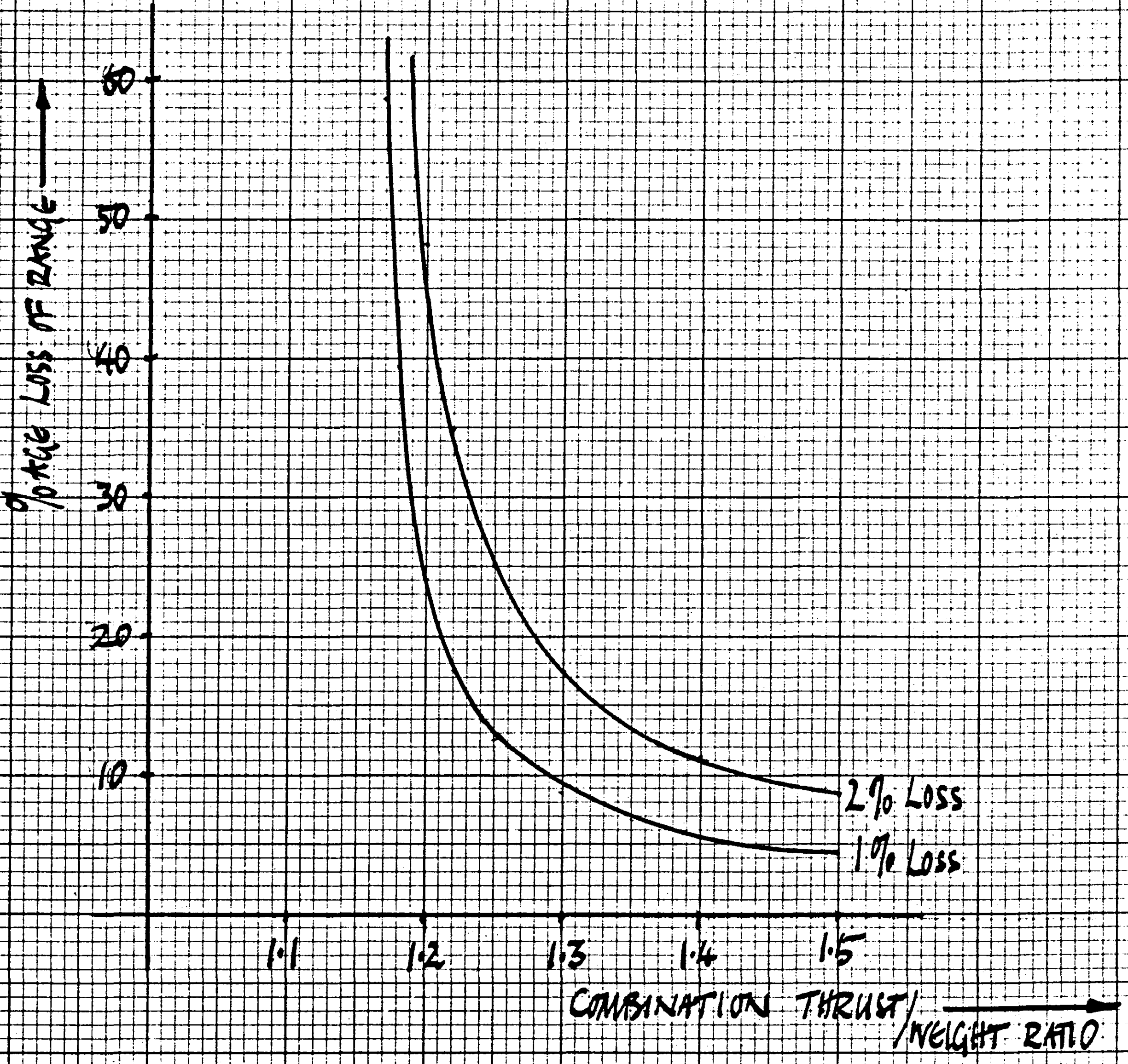


Fig 3: Loss of range for 1% loss of thrust vs thrust/weight.

[Takeoff T/W ≠ 1·15]

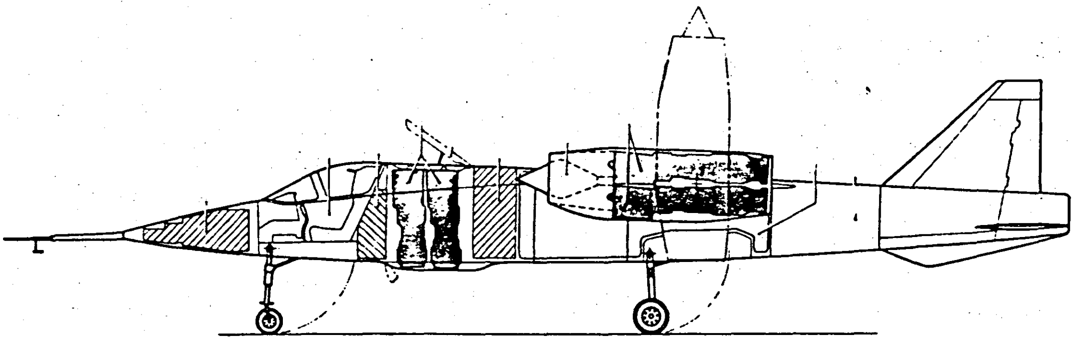


Fig 5: RB 145 Layout in VJ-101-C

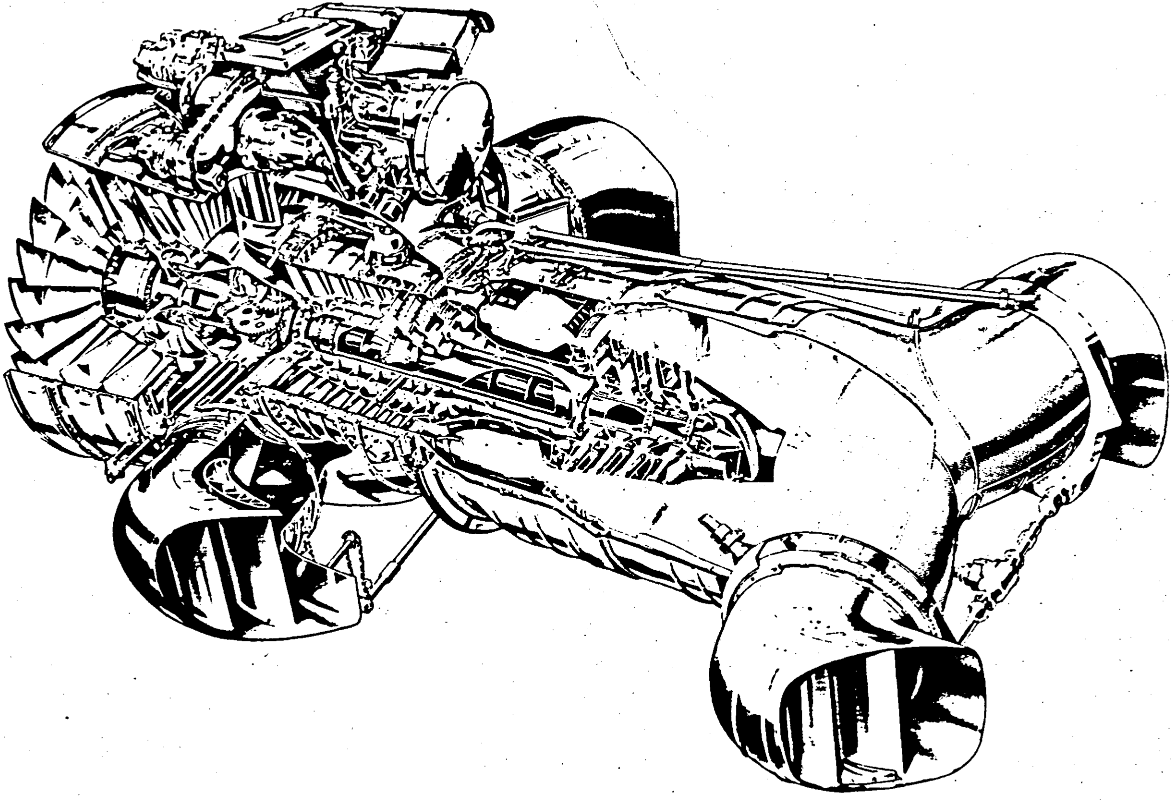


Fig 6: The Bristol Siddley Pegasus

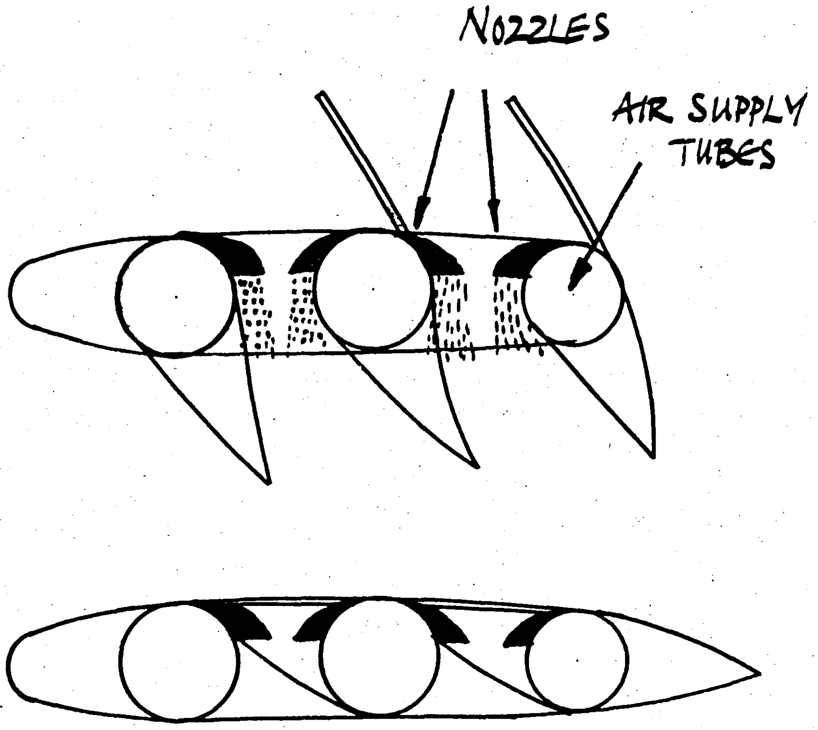


Fig 7: The Augmentor Wing

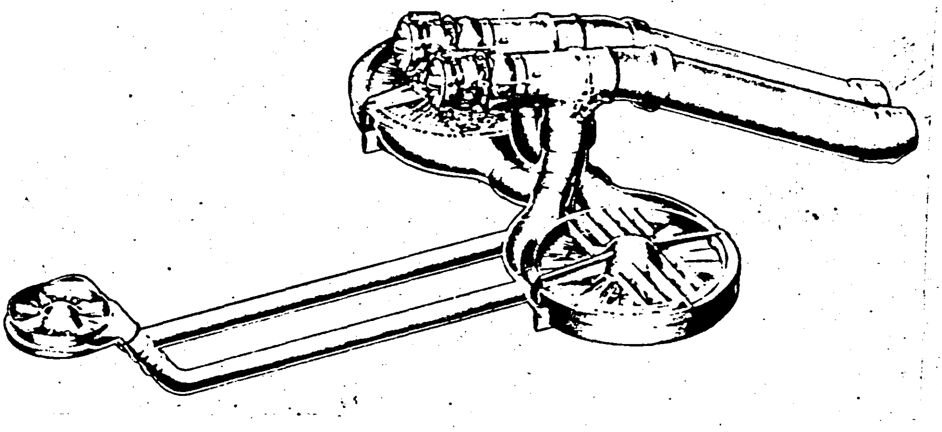


Fig 8: The engine layout for Ryan XV-5A

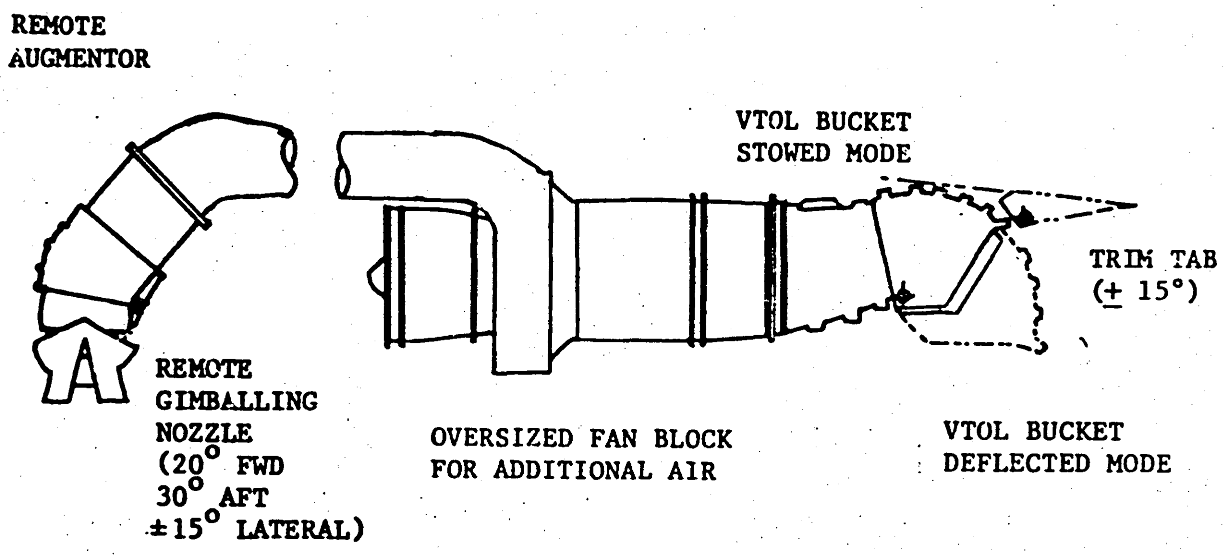


Fig.9: Remote Augmentor Lift System (General Electric Corporation)

SECTION 3. CONTROL, STABILITY AND INTAKE/EXHAUST DESIGN

Control

In normal flight a V-STOL fixed wing aircraft uses aerodynamic flying controls in just the same way as a conventional aircraft. As speed is reduced to the lower limit of wingborne flight and the wing approaches its stalling point, the methods of control of the two types of aircraft begin to diverge, and from the point of stall down to the touchdown they differ altogether.

The conventional aircraft postpones the stall, and keeps its wing working by means of slots, slats, flaps and boundary layer control, the VTO aircraft accepts that the wing will no longer fully support it and transfers the load to engine lift instead. The conventional aircraft never allows its speed to fall as low as the reduced stalling speed of the augmented wing, the VTO aircraft can come to an airborne full stop.

To be able to do this, and to be able to remain under positive control while it does it, the VTO aircraft needs to be equipped with a whole new flying control system for management of roll, yaw, pitch and attitude. This new flying control system brings with it a whole new set of challenges for the designer.

To achieve equilibrium in jet lift the total weight of the aircraft must be equal to the resultant of all the lift forces, and to achieve static equilibrium this must happen with no radial forces left, and the aircraft in an attitude that is acceptable to the pilot, horizontal or nearly so if the aircraft has a conventional undercarriage and landing attitude, nearly vertical if it is a tail-sitter. There is no airflow past the flying control surfaces, so they can offer no assistance in maintaining a balanced hover. The only source of control effort then must be the engines.

These can produce control forces in two ways:

(1) By direct deflection of the efflux at the jet outlets themselves i.e. direct lift control

(2) By adding a further set of outlets at the extremities of the aircraft and exhausting through the compressed air to cause reactive forces or couples, i.e. by use of "puffer-jets".

Direct lift control is not particularly suited to this application. The forces at the nozzles are of necessity large, so fine control would be difficult to achieve. (This might not, however, be quite so important in the case of an aircraft supported by a front lift-jet lift-fan balancing the main engine at the back, where variation of the output of the front engine could offer acceptable control in pitch). Roll control would be particularly coarse and insensitive because the nozzles to be used might be supporting half the weight of the aircraft on each side, and the moment arm available to them would be smaller than that available for pitch or yaw because they would be relatively close together, in the case of lift engines in order to minimize the roll effect of an engine failure, in the case of a vectored thrust engine because of the shape of the engine.

"Puffer-jets" are a lot more attractive. It was to explore the problems control by "puffer-jets" that the Rolls-Royce Flying Bedstead was developed, air from the jets coming from compressor bleed systems on the main engines, and "puffer-jets" provided control power in low speed and the hover for the Bell Vertical Riser of 1955 and its successor, the Bell X14.

In the system used in the Bell aircraft, the nozzles were at the four extremities of the aircraft, and in the neutral control condition each provided equal and opposite thrust upwards and downwards. When a control movement was made, the downward thrust increased by a certain amount and the upward thrust decreased by the same amount. There were two objects in this: one, that as all gas flow changes took place in the nozzle itself, the lag in the control systems was as low as could be, and two, that the total vertical thrust of the entire nozzle system remained constant at zero, so control movements did not have to be accompanied by changes in engine power with their inevitable effect on the attempt to maintain a steady hover weight. It also meant that the ducting from gas generator to the "puffer-jets" could be safely and efficiently designed for constant mass-flow.

On the debit side, there was no net nozzle thrust available to contribute to the total lift requirement as would have been the case if all nozzles kept the aircraft in balance by the exercise of a constant discharge downwards. But, again, if this were so, then control movements would cause flow changes to be made all round the system. This would result in an increased lag between control demand and response, and whether this would be acceptable would depend on the pilot's criteria and on the autostabilization.

Aside from the interaction between control demands and the need for constant hover height, sudden changes in bleed air quantity can cause engine fluctuation and surges, which are best avoided. Ideally a design compromise is reached whereby a constant bleed output is available large enough to cope with normal control demands while occasional excursions into extreme control movements, such as might arise in turbulence or in an emergency are catered for by allowable transient increases in bleed air flow.

Design of the plumbing to take bleed air from the compressor to the jet is where another compromise has to be sought. There is already a loss to be supported in bleeding the air from the compressor of the engine that only just keeps the aircraft airborne; any further loss really should be made as little as possible. The losses in the pipework and ducting are a function of the $(\text{velocity})^2$, which suggests that the ducting should be sized as generously as possible. Weight and space considerations dictate the opposite.

An extreme version of the "puffer-jet" is one with its own reheat system. The sinisterly named 'Bleed-and-Burn' system will enhance the thrust available at the "puffer-jet" by a further 50%. It is described in Ref.(1). A simple "puffer-jet" control system suits aircraft up to an all-up-weight of 40,000 lb. After that, the demands it makes on the engine are too much for it to remain an economical solution to the control problem. A "puffer-jet" system to be effective may call for as much as 10% of the compressor air to keep going. Beyond that point the designer must consider feeding his "puffer-jets" from an auxiliary power unit, as in the first Bell aircraft which used a Palouste, or reconsider some form of direct lift control.

The Fan Lift Aircraft. These problems do not relate to the aircraft which achieves its vertical lift by means of lift-fans in wing and fuselage. In the Ryan XV-5A, control below the stall is accomplished as follows:

Pitch is controlled by varying the position of airflow doors over the lift-fan in the aircraft nose, control for this being by movement of the control column in the natural sense.

Roll is controlled by differential opening of a set of spanwise louvres beneath the wing fans, control coming from sideways movement of the control column.

Yaw is controlled by deflecting the same louvres differentially fore-and-aft, actuation coming from the rudder pedals.

An extra control, corresponding to the collective pitch lever in a helicopter, deflects the louvres symmetrically up or down to vary the total lift when taking-off or landing.

Trade-Offs. The extra complexity and weight introduced by hover control systems in V-STOL aircraft is not entirely without compensation when compared with a conventional aircraft. Against these weight increases may be balanced the lack of necessity for high-lift devices and their actuators, as well as the fact that the conventional control surfaces on a VTOL aircraft need not be large enough to be effective at speeds where the high-lift devices are deployed. Comparisons between the XV-5 and the Buckeye, a fighter aircraft of very similar size, tell their own tale.

		XV-5	Buckeye
Empty weight	(lb)	7540	8500
Max T/O	(lb)	12300	12500
Max.speed	S/L (mph)	547	530
Areas	ft		
	Wing	260	255
	Flap	25	50
	Elevator	12	17½
	Rudder	6½	11

When evaluating these trade-offs account must be taken not just of the comparisons in size of the control surfaces, but also of the scaling of actuators and mountings.

Control Effectiveness

A final difficulty of controlling a V-STOL aircraft in the hover is that movement of the aircraft is neither resisted by aerodynamic damping nor moderated by aircraft stability. A normal aircraft in flight will resist control column movements by natural aerodynamic forces or by artificial feel tailored to reversible natural aerodynamic forces, and by its own inertia. A V-STOL aircraft in jet-supported flight can resist only by inertia, and there are no 'natural' criteria on which to model artificial feel. This all means that the V-STOL aircraft needs some form of autostabilization to assist the pilot in all but the most undemanding flight conditions, and it means too that the control system designer is free to adorn it with any type of response characteristic he chooses.

The question of deciding just what the best response characteristics are for a V-STOL aircraft has had to be tackled empirically. What is required is to equip a V-STOL aircraft with an autostabilization system with variable stability, run a series of experiments, and find out what the pilots like best. Trials along these lines, with the pilot's opinions rated and recorded on a Cooper-Harper scale, have been progressed at the NASA Research Centre, Ames, for some years, using a revived Bell X-14, (now the X-14A), and more recently a rebuilt Hummingbird X-4B, to compile a bank of information on preferred control reaction and responses for VTOL aircraft. (Ref.2, 3, 4, 5).

Problems in the Hover

A helicopter in a low hover at a height of about half a rotor span or below enjoys the benefit of being in 'Ground Effect'. The mass of air pushed downwards by its rotors rebounds off the surface before dispersing and forms a cushion supporting the aircraft. A helicopter can hover in its ground cushion with less power required than at any other altitude; in fact it can hover in its ground cushion yet not have sufficient power to support itself in a hover at any other altitude. It can take off smoothly and progressively and land gently, all thanks to its ground cushion. Unfortunately, no such blessings are bestowed on an aircraft hovering by the support of a number of high speed jets. Instead of stabilizing below the aircraft, as the rotor downwash does in the helicopter, the jet efflux of the VTOL aircraft hits the ground and disperses radially at high speed still keeping close to the ground. In so doing it gathers air in from around itself, and this air, rushing in between the jet wake and the underside of the aircraft, creates a suction whose intensity increases with decreasing height of hover. The size of this suckdown is, in fact, an inexact function of the hover height, the aircraft plan area and the jet diameter. At its worst it can cause a loss of lift of 40%, and its existence accounts for the apparent inability of a VTO aircraft to hover at a height of less than about one wing span, or touch down vertically other than with a final apparent drop.

A helicopter's ground cushion will be dispersed in a light wind or if the hover is over long grass. Fortunately the corollary as applied to the ground effects under a V-STOL aircraft is also valid. Anything that modifies the radial symmetry of the jet/ground interface will reduce the duckdown; a light breeze, channels running along the landing surface and, of course the grid that was a feature of earlier brochures for V-STOL at sea.

V-STOL jets are bound to cause ground erosion if operation is from a natural surface. The amount and severity of this depends on the jet velocity which may range from 500ft/sec under a ducted fan to 1500ft/sec under a pure lift jet. The problems that the P1154 would have brought along with its reheated cold jets and total thrust of 30,000lb from just four jets would have been formidable.

In certain conditions, jet efflux will be reingested by the engines. Hovering into a breeze might bring this about. If this happens and a temperature rise at the inlet occurs, then engine thrust is bound to suffer. A rise of 10^{o}F in the temperature of the intake air can cause a loss of thrust of 3% (Ref.6) and while this might be only serious in a helicopter, for a V-STOL aircraft with jet-lift and a one-to-one relationship between jet-thrust and aircraft weight it could destroy the hover altogether.

One ground effect, however, can be put to good use. Where two or more jets spaced two-to-three diameters apart impinge on a surface, their flows meet at a common line and, having nowhere to escape to but upwards, combine to form a fountain. These fountains will be very hot and must be discouraged from taking the shortest path to the nearest intake, but they can be trapped and used to back off the detrimental effects of suctions. Designing the under-side of an aircraft in such a way as to avoid the harmful interactions and harness the good, is still largely a matter of empirical experiment. Such investigations have led to the appearance under certain members of the Harrier family of patterns of strakes and dams, all intended to improve the performance in hovering flight. Variously called "LIDS" (Lift Improvement Devices) or CADs (Cushion Augmentation Devices), they are a feature of the AV-8B and are also the subject of a series of trials started on the British Harrier in 1978.

Problems in Transition from the Hover

As a VTOL aircraft moves off from the hover it will want to pitch up more and more as its speed increases. There are several reasons for this:

(1) If the aircraft starts off in ground effect, the suction centre will move aft as the symmetry of the efflux spread becomes distorted.

(2) The jets themselves trailing behind will induce air with the same effect.

(3) If lift engines are fitted they will now start to draw air from ahead and expel it faster to the rear so a pitching movement will result from the net momentum change

(4) The intakes may be drawing air from over the wing, thus depriving the wing of the lift it had expected to gain as forward speed increased, so the incidence must be increased to counter this.

And now, as the aircraft tilts backwards, so too does the thrust line of all the lift engines, so they now provide a component of thrust opposing the horizontal acceleration.

These problems are more severe where lift fans are in use because of the larger mass flow involved. Altogether it is all these effects which define the design case for the hover flying control system in pitch.

Fortunately, there are design palliatives for all these adverse effects. The suctions induced aft of the jet outlet can be reduced by the provision of longitudinal fences or strakes in the zone along the sides and behind the exit; the lift jets, if mounted far enough aft on the wing will have a jet-flap effect and increase lift that way as well as by adding to the lift generating circulation around the wing, and they may be tilted slightly forwards to offset the deceleration effect, and the aircraft allowed to hover in a slightly nose-up attitude.

All of these phenomena, and especially those involving interaction between intake flow, exit flow and flow around the whole aircraft can only be investigated and quantified by model experiments. Analytical techniques for unravelling them at the design stage are still awaited.

Engine Exhaust Gas Flows

A lot of analysis has of course already been completed in particular at the Naval Air Engineering Centre at Lakehurst, New Jersey. This has been done because of the need to predict loads due to heat and pressure on ship structural items such as deck panels, Jet Blast Deflectors, and VTOL pads, as well as to establish safe operating distances for flight deck personnel and equipment.

For analysis purposes, four distinct jet regions have been identified.

Region 1 is directly down stream of the nozzle. Here gases are in rapid expansion and entrain large amounts of ambient air. This region extends up to 12 nozzle diameters with jets aft.

Region 2 follows a small transition zone, and complete mixing of the exhaust gases and ambient air has taken place. The flow is commonly referred to as a free jet.

Region 3 is the area of impingement with the surface. It starts about one nozzle diameter above the ground and extends along the ground for some two or three nozzle diameters provided it is initiated by a Region 1 flow. If the aircraft or nozzle height allows a Region 2 flow to develop prior to impingement, the ground portion of Region 3 can extend beyond ten to fifteen nozzle diameters. In this latter case, the maximum velocity along the ground will be less than 10% of that at the nozzle exit.

Region 4 is after transition through another zone during which the stagnation overpressure is spent and the flow is returned to ambient pressure. Flow in Region 4 is sometimes referred to as Wall Jet Flow.

Flow in Region 3 and 4 scrubs along the ground and so a boundary layer will develop. Normally the Region 3 flow is laminar while that in Region 4 is turbulent.

Three terms have come into usage in describing the flow geometry; decay, profile and plume.

Velocity degradation along the jet and/or at the edge of the boundary layer is referred to as Velocity Decay.

The velocity fall off perpendicular to the edge of the jet or the edge of the boundary layer is referred to as velocity profile.

The velocity varies with distance laterally and longitudinally from the core or the flow. A map of iso-velocity lines is referred to as a Velocity Plume.

NAEC's prediction capabilities of jet flows is now claimed to enable the construction of decay, profile and plume diagrams for velocity, temperature and pressure.

FACTORS AFFECTING DESIGN OF INTAKES

Air intakes for the engines of V-STOL aircraft need to be more versatile than intakes for conventional aircraft. The extra demands made of them are as follows:

(1) Intakes for lift engines and lift fans have to be designed to collect air which is above them with the aircraft standing still, and coming past them at 150 knots or more when the aircraft is in the later transition stage of flight, with equal efficacy.

(2) Intakes for lift/cruise engines must pull in an enormous mass flow of air from all around the aircraft when it is stationary, and also cope efficiently with an inflow from forward speeds ranging right up to Mach 2 without causing excessive drag.

Lift Engine Intakes. Lift engines must be limited in their height for installation reasons, so the intakes must be short in length. Pure lift engines have simple axial flow compressors, which demand a smooth uniform air velocity at the compressor face. A poor airflow can lead to surge and possible flame out, and at least to some form of asymmetric loading which will cause fatigue problems and lead to a short engine life. This smooth airflow must be produced from air which has been captured from a fast moving passing airstream and turned through 90°, (or even more if the engine is arranged to tilt in order to provide a component of the thrust required to accelerate or decelerate the aircraft in flight).

While the aircraft is in still air, a symmetrical airflow can be readily established. (Fig.1). Once it is moving forward the fore and aft symmetry is lost because, (Fig.2), the fore half of the intake ahead of the lateral diameter has its supply reinforced by the relative airflow, while the after half has to reverse the direction of its input air which is already going the wrong way when it comes under the intake's influence.

So intake design has to be aimed at reversing this imbalance by means of profiling the leading edge, to obtain a smooth even change of direction, and fitting scoops around the trailing edge, to help reverse the flow. These scoops may also act as doors to cut the intake out when the aircraft is in wing-borne flight.

Conditions are likely to be even worse at the higher end of the transition speed range, as the lift engine will be throttled back as lift is completing being transferred to the wing.

Clearly then, design of a successful lift-engine intake is of great importance to the safety of the aircraft, especially when hovering, in which condition it is at its most vulnerable to loss of control through engine abberations. It is vital too that lift engines should have 100% relight reliability in flight. A V-STOL aircraft making a vertical landing following a short horizontal takeoff is able to do so because it is at a much lower weight, so it is unlikely to have fuel for a diversion to an airstrip, even if one can be found big enough to offer the extravagant landing run that would be required. One problem in guaranteeing a relight is that it is in the nature of the aerodynamic forces above and below the engine to cause it to windmill the wrong way, so the scoop intake must be aided by some aerodynamic form of extractor to reverse this state.

Lift/Cruise Intakes

A lift/cruise engine is horizontally disposed, so it may have a longer intake than a lift engine, so smoothing out the intake flow is less of a problem. This intake has to handle stationary air and supersonic air equally well. The first calls for a well rounded intake profile with a large cross sectional area, the second needs a sharp profile causing very little drag.

The need for the highest efficiency possible is illustrated by the figures describing the intake requirements of the Harrier. At takeoff the Harrier is consuming air at 10 tons per minute. A loss of 1% in intake efficiency will be followed by a reduction of 2% in thrust, and therefore in disposable load. In round figures the takeoff weight of the Sea Harrier is 20,000 lb of which 5000 lb will be fuel. So a loss of only 1% at the intake will cost the aircraft 400 lb fuel and so reduce its range by 8%.

Consider the intake as in Fig.3. The fastest air is that passing closest to the lip, and the smaller the lip radius the faster will be the air going by it. The efficiency of the intake is a measure of how well it can recover the kinetic energy of this fast-moving air in the form of static pressure. The faster the air the more energy is going to be lost in recovery, so it is preferable for the speed of the air to be kept low. This means that the intake profile should be rounded and full for best results in hovering flight, and a sharp profile is totally undesirable.

However, rounded lips will cause unacceptably high drag, especially transsonically.

At one stage of the development of the Kestrel, the sharp lips of the high-speed intakes were wrapped around with a shaped rubber bag which could be inflated during takeoff and landing to assume the rounded profile desired. The maintenance problems associated with this scheme were thought, however, to be unacceptably high, and so another solution was sought.

The Harrier intake now has a compromise rounded profile and extra air for takeoff and hover comes in through a ring of spring-loaded doors around the cowling. These doors stay shut except when exceptional intake mass flow demands are made.

The final design of the Harrier intake is shown in Fig.4. As speed is increased a massive boundary layer builds up along the fuselage sides leading into the intake. It is undesirable that this should reach the fan, so provision is made for it to be drained off through a channel accessed by a spring-loaded flap, which may open only at high forward speeds. At high speed more air is available to the intake than it needs. This air spills outwards around the intake lips, and in order to keep the resultant "spillage drag" as low as possible, their profile is chosen as one that causes supersonic flow and the shock waves associated with it to be tightly localised. A slam throttle closure will cause a large increase in "spillage drag" which will contribute to the desired result of a rapid deceleration, but which must not be allowed to cause an unwelcome nose-up or nose-down pitching movement.

Jet Pipes and Nozzles

The exhaust nozzle of a jet engine has the object of accelerating the flow through it to as high a speed as local conditions will allow. This objective still holds good for a lift or lift-cruise engine. The mass flow has already been settled by the sizing of the engine, and what remains is to make the best possible use of it.

Lift Engine. The nozzles for lift engines must be as efficient as they are in horizontal engines in spite of the complication that, like intakes, they must be kept short, and as their jets are going to impinge directly on a surface or deck it is desirable that they be shorter still. A short nozzle may be almost as efficient as a longer one if the centre-body within it is short and rounded. In extreme cases the required acceleration can be achieved by having the centre-body actually protruding from the jet pipe by a small amount. Practical experiment is the only effective final design aid.

Lift/Cruise Engines. In vectored-thrust engines the nozzles must be capable of varying the direction of the flow through 90° or more without loss of efficiency in the process. This may be done by:

(1) A right-angle twin nozzle swivelling about a lateral axis (Fig.5).

(2) One or more rotary oblique joints along the length of the jet pipel (Fig.6).

(3) An obliquely mounted set of swivelling louvres, like a section of a venetian blind (Fig.7).

(4) A straight jet pipe with a scoop or clamshell mechanism capable of diverting the gas flow through a trapdoor in the base of the jet pipe (Fig.8).

All thrust vectoring systems in use or projected use one or more of these methods. All have to be evaluated by model tests. (Ref.7.)

Use of reheat or Plenum Chamber Burning requires that the nozzle must have a variable area in addition to all its other properties. In the system developed for the BS 100 a ramp mechanism provided the variable area facility with the nozzle pointing back, and maximum area was fixed with the nozzles pointing down, it being assumed that hovering would invariably be exercised with PCB selected ON. (Recent discussions with Propulsion Development staff at Rolls-Royce (Bristol Division), held in late July 1979, indicate that the control power in pitch of the projected VTO aircraft with which they are currently concerned is now sufficient for equilibrium to be maintained with safety regardless of whether cold nozzle PCB is ON or OFF).

Recent US Developments

Two nozzle designs of interest which it is thought might reappear in certain forthcoming designs in the USA are the scoop type described in Ref.9 and the much more recent slide-valve, described in Ref.10. Sketches of them appear as Figs. 9 and 10.

A third design, and one showing great potential is the Augmented Deflection Exhaust Nozzle (ADEN). If a nozzle exhausts right behind the trailing edge of a lifting surface, extra air is entrained over that surface, the circulation around the wing is increased, and the Lift Coefficient with it. Model tests of rectangular section (Aspect Ratio up to 11:1) nozzles show that the inevitable penalty in terms of Drag is much less than would be expected if the lift increment were obtained by any other means. Downwards vectoring of the exhaust increases this lift augmentation and also of course produces an extra lifting force by virtue of its deflection. This property can be used in flight for lift and manoeuvre enhancement, deflection being brought about by the Variable External Expansion Ramp (VEER), and the exhaust can be fully vectored for VTOL use (Fig.11). A companion to the ADEN nozzle is the General Electric ALBEN (Augmented Load Balanced Exhaust Nozzle), and both these feature in current projections for possible high performance VTO aircraft for the US Navy.

Such an aircraft is depicted in Fig.01. At takeoff the ADEN nozzles deliver approximately two thirds of the lifting force, the balance coming from the forward RALS (Remote Augmentation Lift System) nozzle behind the cockpit. Takeoff is accomplished in two stages. First the nose is lifted by the RALS nozzle at intermediate power. This lifts the main engines intake clear of the rebounding exhaust. Then, when a nose-up pitch angle of 20^{o} is established, full lift-off power is applied and that attitude is maintained up to the beginning of transition to horizontal flight.

Summing-Up

A V-STOL aircraft in the hover has no freestream airflow passing around it so there is no medium on which conventional flap-type flying control surfaces can obtain a purchase; nor any natural damping or stability. There must be an extra control system installed to cope with these conditions, and the type favoured is one using reactive "puffer-jets". The weight of this system is partly offset by the removal of the need for the conventional flying controls to be powerful enough to work right down to landing speed, and for high lift devices to be fitted. The response characteristics of the reactive control system may be chosen by the designer to meet any required specifications.

In hover and in transition there arise interactive forces between the flow around the aircraft and that between the aircraft and the ground. These cause suctions and pitching forces that make extreme demands on thrust and control power to overcome. A high hover height, compared with a helicopter, is necessary for safe operation. Jet effluxes cause suction but they can also generate fountains, which although hot and harmful if allowed to get into the intakes, can be put to good account by fitment of Lift Improvement Devices, Cushion Augmentation Devices or leading edge extensions.

For a lift plus lift-cruise installation, the design should meet the following requirements:

a. The VTOL thrust vector should be close to the C of G to avoid oversizing hovering control mechanisms

b. To minimize ingestion the intakes should be high and the jet nozzles also, which implies a high wing design.Intakes and nozzles should be far apart.

c. Minimum control power should be necessary in the hover so that any engine failure is survivable.

d. Control power at zero speed should be provided by the Lift engine to avoid complicating the Lift-Cruise engine.

Intakes must cope with an enormous quantity of air when the air craft is stationary and yet not cause unnecessary drag at high speed. Jet pipes might have to be able to deflect the entire jet efflux through 90° or more without incurring undue energy losses. In lift engines, the need for a low installed height means that intakes and jet pipes must be shorter than normal.

Finally, the ideal means of designing is one that produces the best configuration without needing recourse to all the empirical model-testing that is still necessary today. This means is not yet to hand, but progress is being made towards its achievement, although even this is still more in the nature of a challenge than a target. NASA Ames is cautiously optimistic:

"Five years of development lie ahead before designers of V-STOL aircraft, and particularly supersonic fighters, can predict performance instead of building prototypes".

That was said in 1977, (Ref.11), but it would be optimistic to expect answers to all the questions within the next two and a half years.

FIGURES

SECTION 3

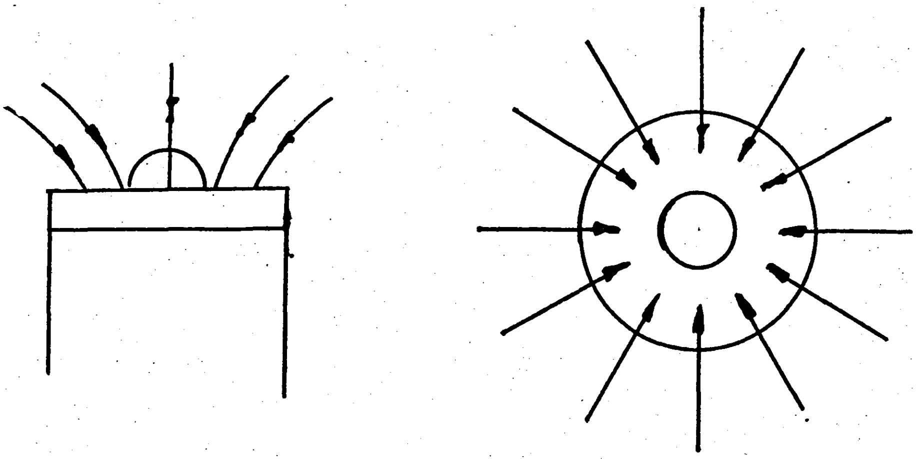


Fig 1. Lift engine intake with symmetrical flow

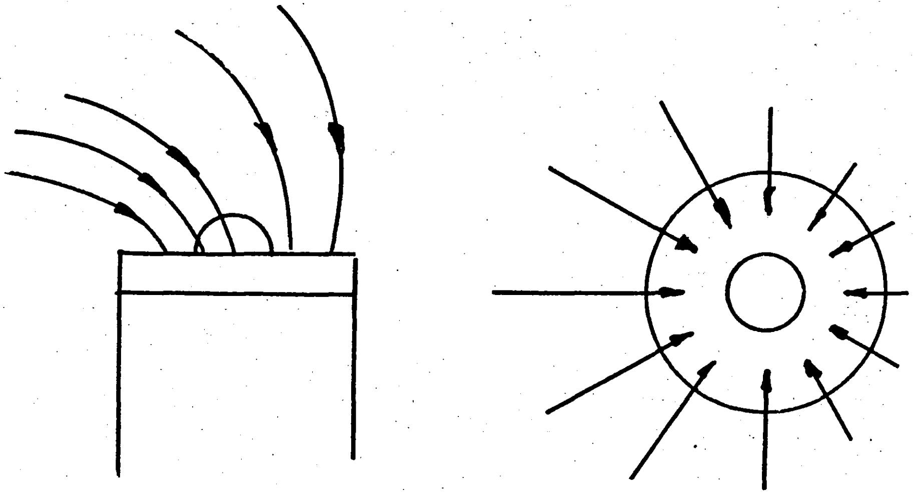


Fig 2. Lift engine intake in forward flight

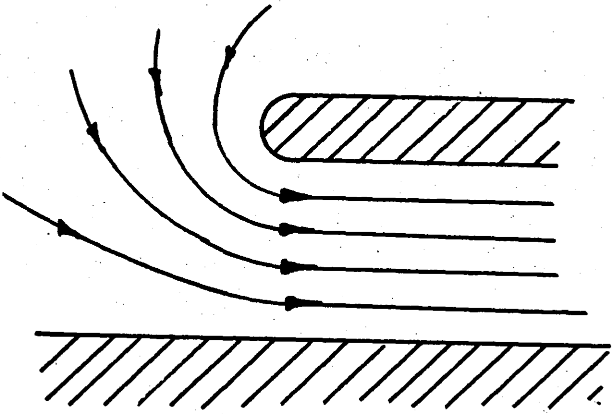


Fig 3. Harrier-type intake flow

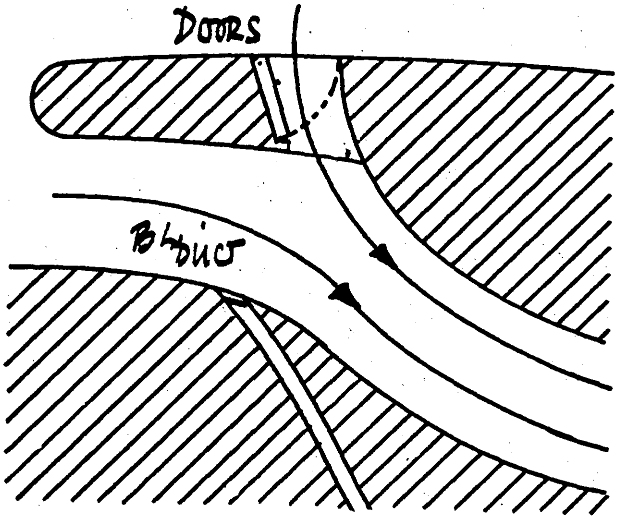


Fig 4. Harrier-type intake with extra doors

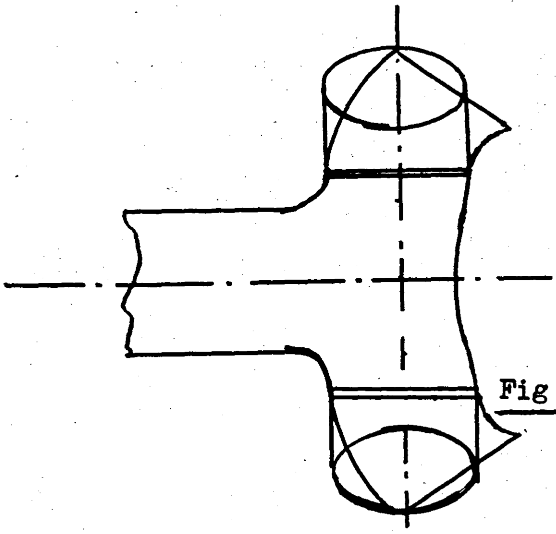


Fig 5. Lateral right-angled nozzle

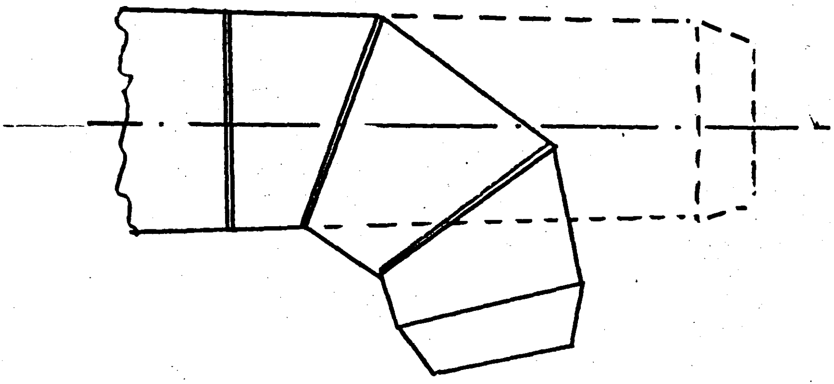


Fig 6. Nozzle with oblique joints

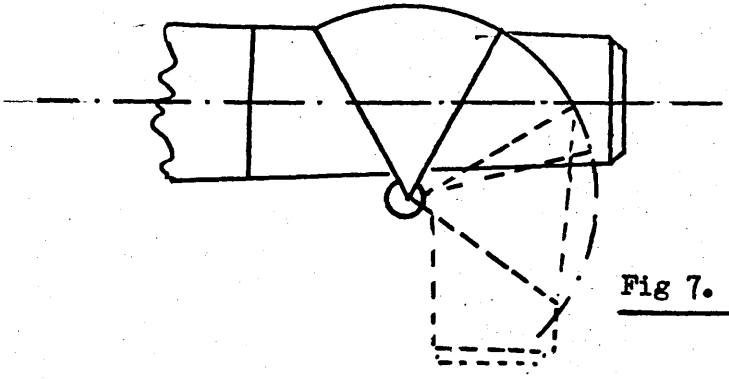


Fig 7. Nozzles with deflectors

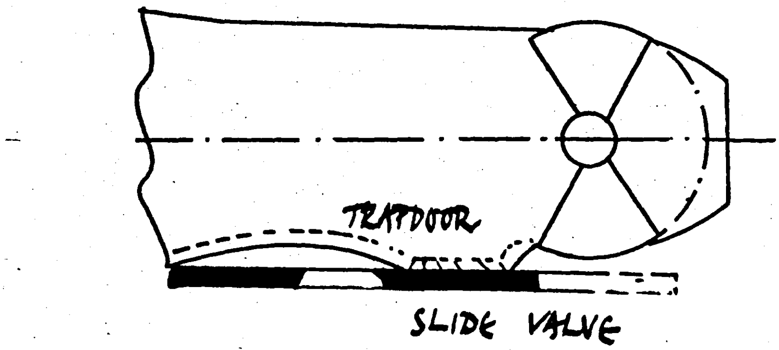


Fig 8. Nozzle with clamshell and trapdoor

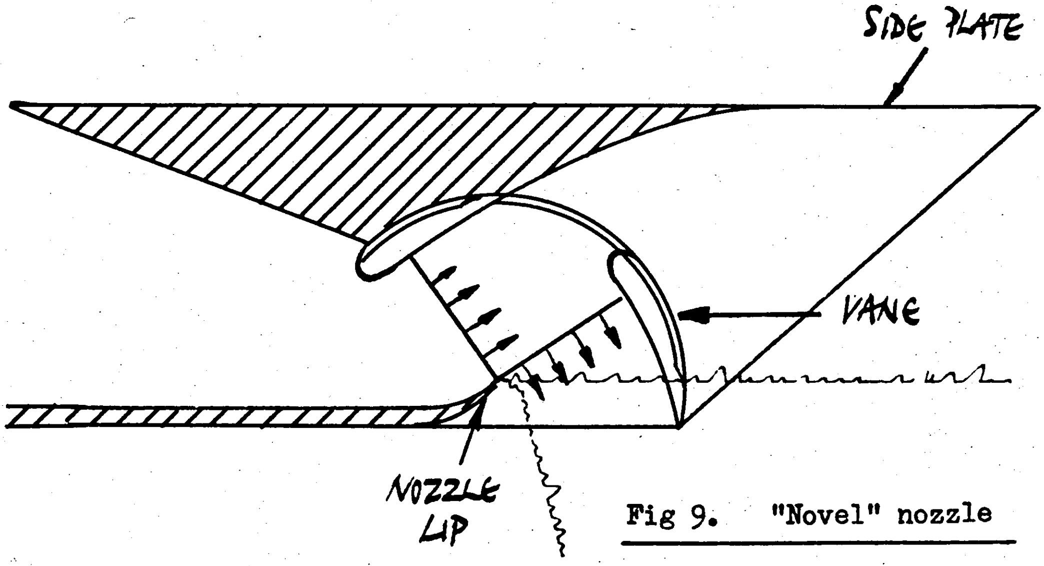


Fig 9. "Novel" nozzle

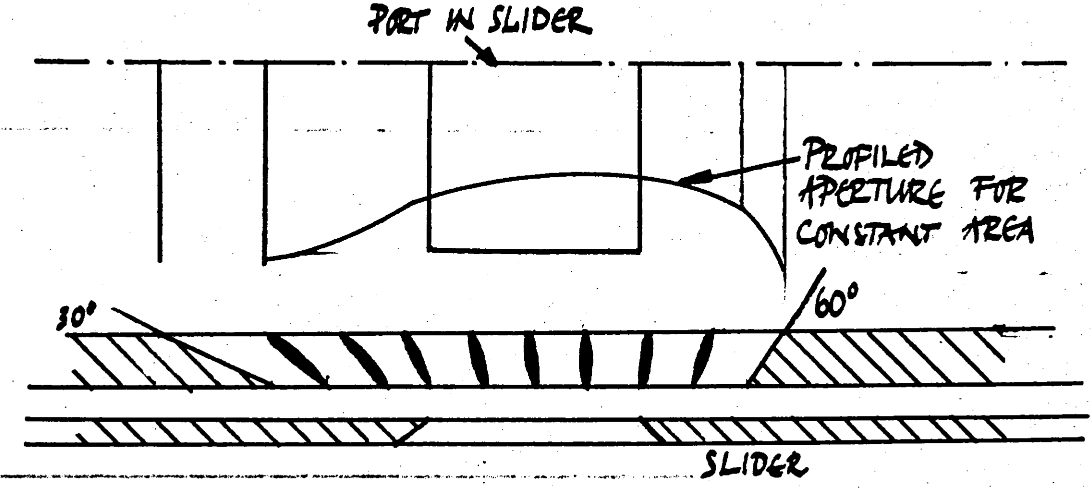
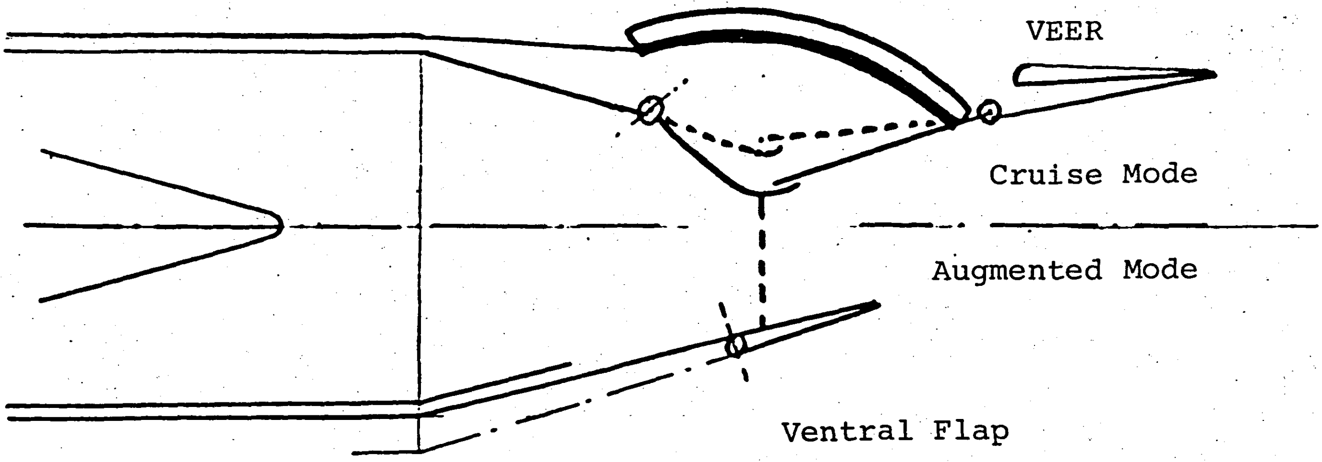


Fig 10. Slide valve nozzle

CRUISE MODE



VTO MODE

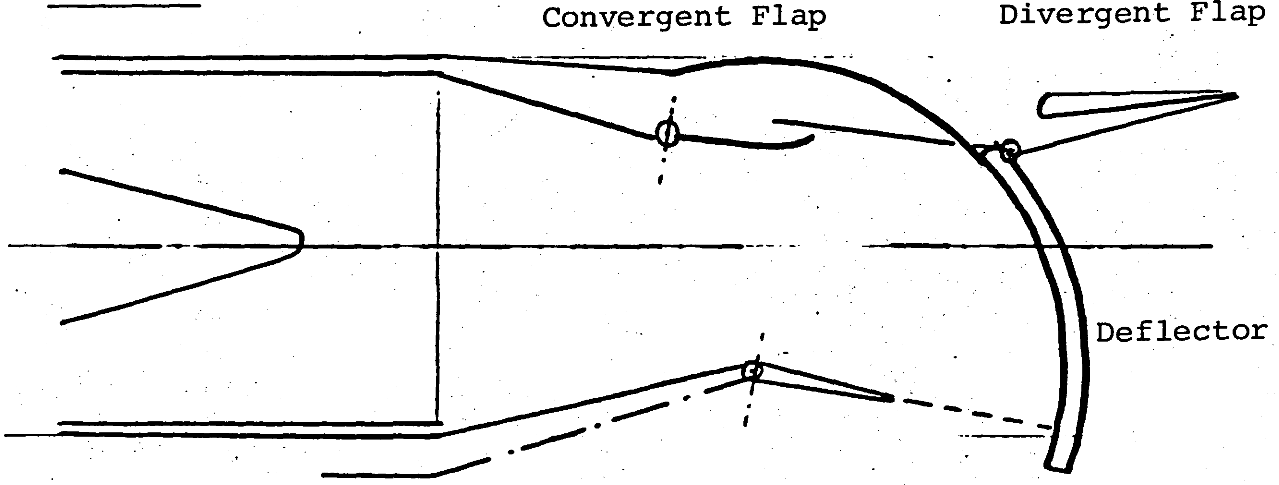


FIGURE 11. Augmented Deflector Exhaust Nozzle

SECTION 4. NOTEWORTHY AIRCRAFT TYPES

There have been little more than a dozen types of jet VTOL aircraft actually designed and built since the days of the Rolls-Royce Flying Bedstead. Most have been prototypes intended solely for research, a few have been aimed at meeting a military specification such as the possible requirement for the Fiat G91 successor to have V-STOL capability, or the NATO Basic Military Requirement -3, only one, the Harrier, has met with success and been ordered and delivered in quantity. These aircraft are introduced here as examples of what could have been achieved, and of how a single specification can be met with widely-differing mixtures of power plants.

Some of these aircraft are alluded to in the articles and features listed in the Bibliography. If the reader is unsure of the difference between the X-14 and the XV-4, the VJ 101-C and the VJ 101-D, or has wondered why an aircraft should be known as the EWR VAK-191-B, this section may be of help. For ease of reference, aircraft are grouped under headings of country of origin, in the order USA, USSR, Germany, France, Italy and Great Britain.

Jet V-STOL Aircraft of the USA

1. The Ryan X-13 Vertijet. (Fig.1)

The Vertijet was a true vertical-attitude takeoff aircraft powered by a single Rolls-Royce Avon of 10,000 lb thrust, giving it a Thrust/Weight ratio of 1.3:1. Initial flight trials started in December 1955 at Edwards Airforce Base with the aircraft taking off and landing on a conventional undercarriage, and it performed its first vertical takeoff in May 1956, followed by a vertical recovery onto a nylon rope between two gantries engaging a hook under the aircraft nose.

Control in the vertical attitude was by pure exhaust deflection and it is reasonable to suppose that wind limitation for launch and recovery must have been very severe. Successful transitions were made from vertical flight to horizontal flight and back to vertical in 1958 and later that year, with research completed, both prototypes were retired to museums, one to the Smithsonians Institute, the other to Dayton, Ohio.

2. The Bell X-14 (Fig.2)

The Bell X-14 was the successor to the quaint Vertical Riser mentioned in Section 2. In its original form as pictured it was powered by two Bristol-Siddeley Viper engines, (the Viper at that time being a lightweight short-life engine, intended for use in the Djindvik target aircraft), and continued the research work started by its predecessor. Its first hover was in February 1957 and its first transitional flight was in May the following year. In free flight it could achieve 160 mph. Its test programme was completed in 1959.

In 1962 it was revived at the NASA Research Centre, Ames, at Moffat Field as the X-14A. Powered now by two GE 7-85-5A engines with more thrust, more air-bleed capacity and less weight than the original Vipers, it was used for research into varying control responses and damping in hovering flight (Ref.1). It was subsequently fitted with an autopilot and continued its work as the X-14B. (Ref.2).

3. The Lockheed XV-4A (Fig.3)

The Lockheed XV-4A (Hummingbird) resulted from a research contract raised in 1961 for two small research aircraft to look into augmented jet ejector lift. Each aircraft was powered by two Pratt and Whitney 12A-3 engines, producing a total thrust of 6000 lb, and for hovering flight, diverter valves in the jet pipes turned the whole jet efflux through 180° into side-by-side ejector ducts running the full length of the fuselage. It then was caused to discharge down through twenty rows of multiple nozzles into two ejector chambers. Above and below these were bomb-bay-type doors which opened during hovering and transitional flight allowing passage to the air entrained by the ejector jets, this air picking up momentum and augmenting the thrust, Although the thrust mechanism denied use of the fuselage volume for anything else, a military version of the aircraft was planned, with armament being carried in underwing pods. Control in the hover was by reactor jets at nose, tail and wing tips.

The aircraft is recorded as having had a max VTO weight of 7200 lb, so evidently the system, fed by 6000 lb thrust, did work but the augmentation does not appear to have reached the 40% expected. If a thrust/weight ratio of as low as 1.1:1 was called for, the net augmentation would have been

$$\left[\frac{7200 \times 1.1}{6000} - 1\right] \times 100\% \quad = \quad 32\%$$

The XV-4A first carried out free hovering flights in the summer of 1963 and its first transition was in November of the same year. One of the two prototypes crashed in 1964 and the programme was discontinued as "circumstances did not allow the continued development of ejector technology and improvements in the ducting which would have produced a flight/weight ejector system".

The surviving prototype was completely converted for use as a variable stability jet lift research aircraft. It was gutted of its engines and ejector system and fitted instead with six J85-GF-19 engines of 3015 lb thrust, four for lift and one either side for cruise. As the XV-4B (Hummingbird II) its first free flight was in September 1968. Unfortunately it was destroyed in a crash in 1969.

4. The Ryan XV-5A (Fig.4)

The United States Air Force placed a contract with the Ryan Aircraft Corporation in 1960 to develop the Vertifan system, and the resulting aircraft, the XV-5A first flew in 1964. Power came from two J85 engines of 2658 lb thrust, and in sub-stall flight the jet efflux from their engines drove two 5'2" diameter fans, one in each wing, and a smaller one in the nose. The method of fan drive was by means of turbine blades around the fan periphery and each engine supplied just half the power. The engine intakes were on top of the fuselage where their influx would conflict as little as possible with the flow into the fans.

The first flight phase was satisfactorily completed by the end of 1964, and one of the two aircraft built crashed in April 1965. The surviving aircraft was used to develop a system by which power during transition from fan-supported to wing-supported flight was transferred one engine at a time, then it too crashed in October 1966.

It was rebuilt as the XV-5B, and transferred to NASA control at Ames, Moffat Air Force Base for use in further research.

5. The US/FRG Projects

See under EWR, later

6. The Rockwell XFV-12A (Fig.5)

This aircraft is boldly planned to be a Mach 2+ interceptor able to operate from the deck of a medium sized destroyer. It is powered by a single Pratt and Whitney F401-PW-400 engine whose jet efflux is all directed forward to ranges of lift augmentation nozzles in the wings and canard foreplane for lift during vertical takeoff and transition. For economy of design and build, some of the major assemblies of the prototype aircraft were expropriated from existing aircraft. Notably its front fuselage and main undercarriage is that of the A-4 Skyhawk while its wingbox structure is that of the F-4 Phantom II.

Its major dimensions are 28 ft span by 43 ft length and its planned maximum weight for Vertical takeoff is 19,500 lb.

Its first free untethered flight is, at the time of writing, some four years overdue. A main reason for this is that the expected value of thrust augmentation the system is intended to produce has not yet materialized. It seems that the interactions between the various primary and induced lifting airstreams still need to be unravelled. If and when it succeeds, it will be the only wholly fresh design under construction in either the US or the UK defence industries.

Jet V-STOL Aircraft of the Federal German Republic

1. The EWR VJ101-C-X1 (Fig.6)

EWR is an abbreviation for Entwickslungsring (Süd) the collective term for an amalgamation of the design teams of Bolkow/Heinkel and Messerschmidt, set up in the early 1960s to collaborate on the creation of a Mach 2 interceptor aircraft.

As a stepping stone to this they first built the VJ101-C-X1 which was powered by six RB 145 engines disposed two vertically in the fuselage and two in two pairs in swivelling pods at the wing tips, producing power for vertical lift as well as horizontal flight. The RB 145 was a descendent of the RB 108, producing 2750 lb compared with the 2010 lb of its precursor.

Control in the hover was by direct thrust modulation, and to bring this about, the throttles were coupled to the flying controls. The VJ101-C-X1 first hovered, then achieved in-flight transition in 1963, but was destroyed in a crash in September 1964. (Ref.4.)

2. The EWR VJ101-C-X2

The immediate successor to the-X1,this aircraft shared the same configurations but its podded wingtip engines had after-burners, raising their thrust from 2750 lb to 3650 lb. This first flew on 12 June 1965 and performed the first vertical takeoff with reheat in October 1965, at a takeoff weight of 17,635 lb and thrust/weight ratio therefore of 1.16. It became the first-ever VTO aircraft to achieve supersonic level flight. (Ref.5).

3. The EWR VJ-101-D (Fig.7)

This was the aircraft towards which the research results of the -C-X1 and -C-X2 had been directed. It was to be powered by four RB 162 lift engines in the fuselage and two RB/MAN 153 turbofans, one either side of the fuselage. The design was never completed, being abandoned for a more ambitious two-seater aircraft to be produced in collaboration with Fairchild/Hiller of the USE (Fig.8). This, too, never came to anything.

4. VFW VAK-191-B (Fig.9)

VFW, (Vereinigte Flugtechieche Werke GmbH), was formed in 1963 out of FockeWulf and Weser. In 1964 they embarked on a study with EWR and Fiat of Italy into a replacement for the Fiat G91, the aircraft to be a subsonic tactical reconnaisance fighter with V-STOL capability.

It was designated VAK-191-B. VAK (Vertical Startendes und Augklasungs Kampflugzeng) translates as Vertical Takeoff and Landing fighter, 191 indicates successor to the G91 and B shows it to be the second international study of such a project. (VAK-191-A) was the Hawker P1127). Power was to come from two RB 162 lift jets in the fuselage plus a deflectable RB/MAN 193 engine for lift/cruise.

Originally there were six prototypes to be built, three single-seat aircraft by Fiat and three two-seat aircraft by VFW. In 1968 Italy withdrew from the project and it was decided that the remaining three prototypes should be used as systems test beds for the Panavia MRCA, later to be named the Tornado.

A successful series of flight trials started in September 1971, and the US Navy took an active interest in the aircraft in 1975, but it was never developed for service use.

Jet V-STOL Aircraft of France

1. The Dassault Balzac V-001 (Fig.10)

The Balzac V-001 was built for the purpose of studying problems of vertical flight and to develop a control system for the Mirage III V, the close rival to the P1154 in the NMBR-3 competition.

It was built from the Mirage III prototype. Removing the original SNECMA Atar engine left room for a Bristol Siddeley Orpheus propulsion engine and a battery of no less than eight RB108 lift engines. Its flight trials began in 1963 (Ref.7.).

2. The Dassault Mirage III V (Fig.11)

This aircraft was configured the same as the Balzac, the engines this time being eight RB 162s of 4000 lb thrust a piece for lift and one TF 106 at 19,800 lb for cruise. The first prototype started its hovering trials in 1965, the second flew in June 1966 and was written off in a crash in November 1966. With the cancellation of the P1154, the NMBR requirement fizzled out, and no plans were made to develop the Mirage III V for production standards, or build further prototypes. (Ref.8).

Jet V-STOL Aircraft of Italy

While Italy never produced any autonomous VTOL jet aircraft, Fiat participated in the VAK-191-B project until withdrawing in 1968, and also planned two contestants for the NMBR-3 competition, the Fiat G94/4 and the '6-cylinder version', the Fiat G95/6. They were to be powered in Lift/ Cruise by two RR MAN 153 engines in the after end, each deflectable and producing 6850 lb static thrust, and four or six (respectively) RB-162-31 lift engines, now producing 5000 lb compared with the 4409 lb of the 01 version, disposed along the fuselage in two pairs or two groups of three. Neither aircraft was ever actually built, remaining only as design studies when Fiat became Aeritalia in 1969. (Figs 12 and 13).

Jet V-STOL Aircraft of the USSR

Russian interests in V-STOL fighters first materialised in an Air Show in 1967 at Domodedovo, when Mikoyan and Sukhoi demonstrated two STOL aircraft, the Mikoyan contribution being basically a Mig 21 with two lift engines additional (Fig.14), and Yakoleb showed a VTOL aircraft originally designated YAK-36 and codenamed Freehand.

Of the Mikoyan and Sukhoi prototypes nothing more was heard, but from the Freehand developed the Forger, the only Jet VTOL aircraft in service in the world other than members of the Harrier family. The Forger A (single-seat) and Forger B (two-seat) made their debut in the Kiev, the first of the Kuril-class aircraft carriers. (Fig.15). They are of about the same wingspan as the Sea Harrier but about 5 ft longer, and are powered by two lift-engines abaft the cockpit and a single Lift/Cruise engine, exhausting through two vectoring nozzles aft of the wing. Analysis credits the lift engines with a thrust of 5000 lb each and the non-afterburning main engine with 17,000 lb.

Curiously the aircraft is always seen to takeoff vertically to a hover height of 15-20 ft then slowly execute a transition to wing-borne flight; a rolling takeoff seems to be unknown.

Jet V-STOL for the U.K.

Development of VTOL aircraft in the UK has been along two lines, the lift-and-cruise Short SC1 and the vectored thrust Harrier family.

1. The SC1

This famous aircraft (Fig.16) first flew in 1957. It was powered by five RB 108 engines, delivering just over 2000 lb thrust from a weight of 269 lb. Four were grouped around the centre of the aircraft and provided lift, while the fifth in the tail propelled the aircraft in forward flight up to 250 knots. The battery of lift engines were capable of being tilted fore-and-aft through a range of 35° in order that they should contribute to forward acceleration and deceleration.

Flight control in hover and transition was by reaction jet nozzles in tips, nose and tail, all controlled from an electrohydraulic autostabilization system. Although one of the two aircraft produced crashed in 1963 during an autopilot test, it was rebuilt and both aircraft finished their service career in the hands of the Aeroflight Division at R.A.E. Bedford. The one crash notwithstanding, (which was not due to any phenomenon associated with vertical takeoff and landing) both aircraft thoroughly proved the concept of using small lift-jets for takeoff and transition, switching them off for forward wing-supported flight, and reselecting them again, confident that they would always start, preparatory to coming once more to the hover and landing.

2. The Harrier Family

As has been related in earlier sections of this paper, the Harrier family started with the Hawker P1127, built as a private venture to house the BS 53 vectored-thrust engine, itself a private venture as far as UK government funds were concerned. The 1127 became the Kestrel and a successful tripartite USA/FRG/UK squadron formed in 1964 to assess the aircraft as a working flying machine. When the squadron disbanded, its period of operation profitably complete, six of the aircraft went to the USA for evaluation by the US Army, Navy and Air Force, taking on the designation AV-6A. This complete, four went on to become the subject of further study and research at Edwards Airforce Base, the other two to Langley Aviation Research Centre.

Meanwhile, the specification which fostered the growth of the 1127 was formally issued as NMBR-3, and the P1154, a single-engined supersonic derivative of the 1127 design was schemed (Fig.17) to meet it. Cancellation of the P1154 by the new government in 1964 led to the decision to develop the Kestrel into a proper military aircraft, and the Harrier was born, lifted by the Pegasus 6, at 19,000 lb thrust a far cry from the BS 53 at 13,500.

US interest in the aircraft bore fruit when in 1970 the US Marine Corps took delivery of its first dozen Harriers MK50, the engine now having been extended to 21,500 lb with even more in hand. The USMC went on to procure four squadrons of what was then designated the AV-8A. By January 1976 the

USMC had accumulated well over 42,000 flying hours on the type, and six, plus two trainers, were delivered to the Spanish Navy where they go under the name of Matadors.

The aircraft was still ripe for development and in 1973 studies began on two particular extensions, an Advanced Harrier and a Naval Harrier.

a. The Advanced Harrier

In 1971 Bristol Siddeley engines agreed to carry the development of the Pegasus engine further in conjunction with Pratt and Whitney. Increase of fan diameter by 2" together with other sizing improvements would take the thrust up to about 25,000 lb. The aircraft for this would be the AV-16A, but the UK pulled out in March 1975, leaving airframe design leadership with McDonnel Douglas in the USA. The USMC also withdrew on financial grounds, but settled instead on procuring an aircraft with the existing Pegasus 11 engine, but incorporating the advanced aerodyanmics, structures and weapon-systems as proposed for the AV-16A. The aircraft that results, the AV-8B (formerly the AV-8+), includes the following improvements over the AV-8A:

(1) A new supercritical wing, made in composite materials and although nearly 6ft bigger in span, weighing 330 lb less, and able to carry more fuel.

(2) A new engine intake with oval rather than semicircular cross-sections and double-doors rather than single doors, adding 600 lb thrust.

(3) Lift-Improvement Devices (LIDs) comprising a retractable crossdam linked with the undercarriage, and fixed strakes running longitudinally behind it, increasing the VTO capacity by 1200 lb.

The first two aircraft were built by conversion from existing AV8As and called YAV-8Bs, (one of which crashed in November 1979). The USMC originally hopes to buy more than 300.

b. The Naval Harrier

The Sea Harrier programme was approved in May 1975, for an aircraft to be based on the Harrier FGR Mk III. The weapon system changes reflect a change in role from ground support to a potential for air-to-air combat as part of a Fighter/Recce/ Strike package, there is no inertial navigation system, and boldly, the undercarriage remains the same. Navalization has been limited to the addition of extra tie-down points and the elimination of corrosion-eager Magnesium alloy components, all costing only 0.5% increase in the aircraft operating weight empty. The Sea Harrier has 15% more control power in roll, and incorporation of more weapon system and radar equipment has accompanied improved all-round visibility from the pilot's seat. Otherwise it is very little different from its land-based cousin.

The Sea Harrier Intensive Flying Trials unit was formed in July 1979.

Summing Up

More than a dozen different types of jet VTOL aircraft have been built and flown during the last twenty-five years, while many more have been designed to meet NATO requirements that were never followed through. Of those which flew, more than half were purely research and experimental aircraft, all the American X-series, the VJ-101-C, the Balzac, the SC1, while, of the remainder two fell by the wayside, the Mirage III V and the VAK-191-B, demonstrated but not developed. Only two got into service, the Harrier and the Forger, and the Rockwell XFV-12A remains a dark horse still.

The table below lists the main measurements and proportions of the new VTOL fighter/ground attack aircraft intended for operation at sea.

	AIRCRAFT			
	SEA HARRIER	AV-8B	XFV-12	YAK-36
owerplant	Pegasus V/T	Pegasus V/T	F401 Augmented	1 Main, 2 Lift
-TOL rating (Kg)	9,000	9,500	13,600	1 x 8000 + 2 x 3600
pan (m)	7.70	9.24	8.69	7.65
ength (m)	14.5	13.07	13.39	16.2
mpty wt (Kg)	5,500	5,620	6,260	7,000
OL wt (Kg)	11,500	13,350	8,840	10,000
evel Max M	0.9	0.9	2.0	1.05
nternal Fuel (Kg).	2,865	4,175	2,763	3,000

The success of VTOL aircraft at sea in the next decade will be the success of one or more of the aircraft listed above.

Finally, the ideal means of designing is one that produces the best configuration without needing recourse to all the empirical model-testing that is still necessary today. This means is not yet to hand, but progress is being made towards its achievement, although even this is still more in the nature of a challenge than a target. NASA Ames is cautiously optimistic.

"Five years of development lie ahead before designers of V-STOL aircraft, and particularly supersonic fighters, can predict performance instead of building prototypes". That was said in 1977. (Ref.11), but it would be optimistic to expect answers to all the questions within the next two years.

FIGURES

SECTION 4

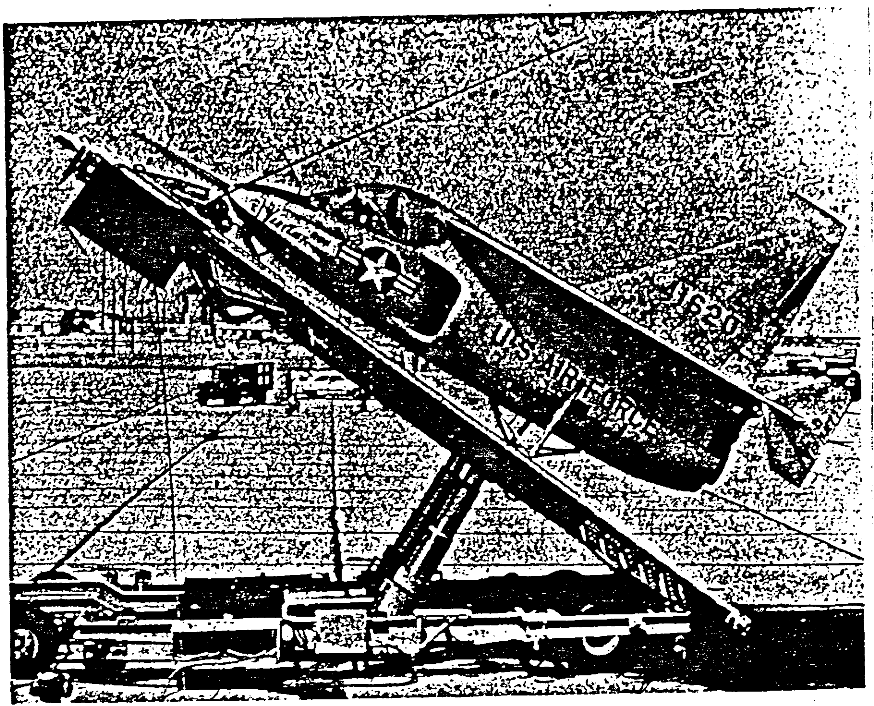


Fig 1: Ryan X-13 Vertijet; single Avon

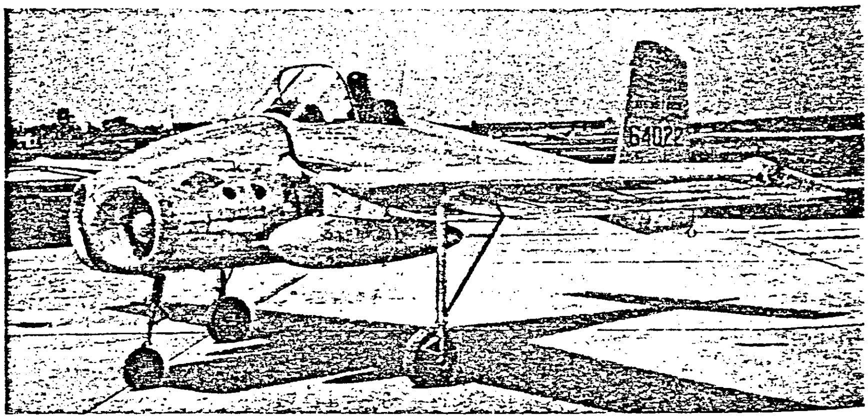


Fig 2: Bell X-14; twin Viper

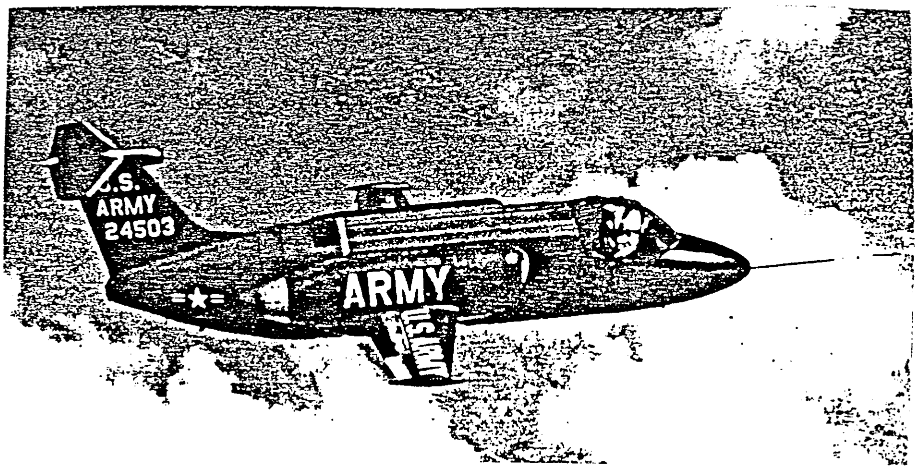


Fig 3: Lockheed XV-4A 'Hummingbird'; two P+W JT12A-3s

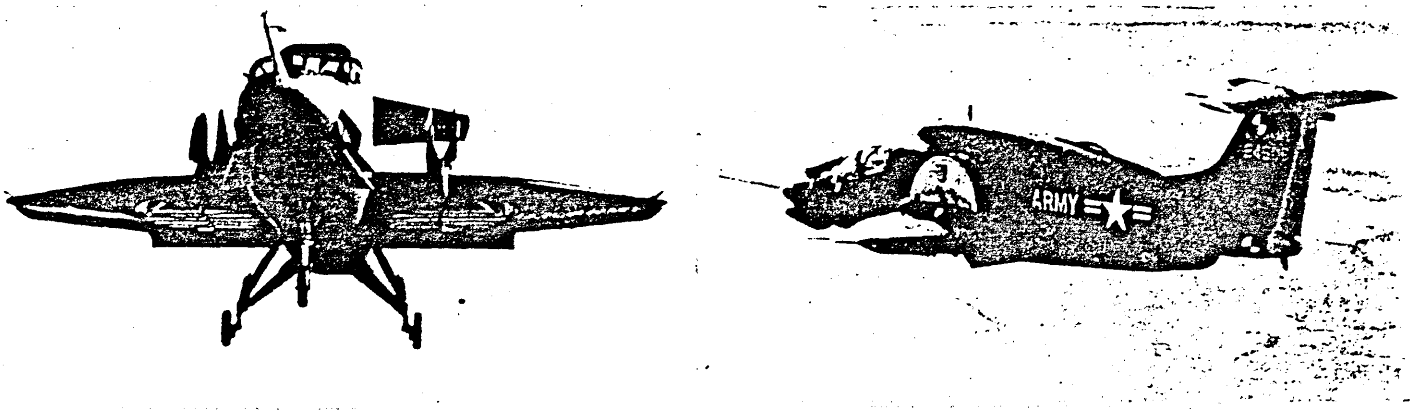


Fig 4: Ryan XV-5A Fan-in-Wing; two J85s

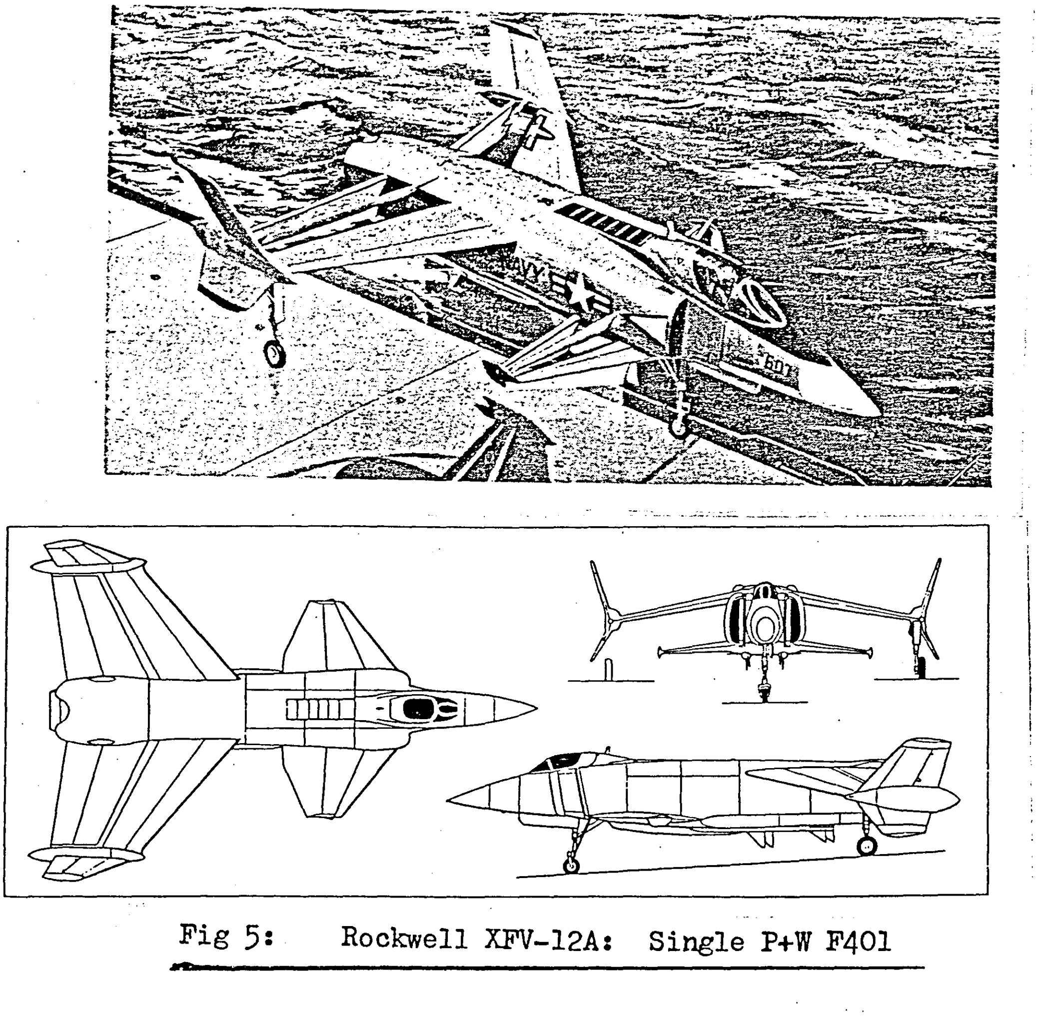


Fig 5: Rockwell XFV-12A: Single P+W F401

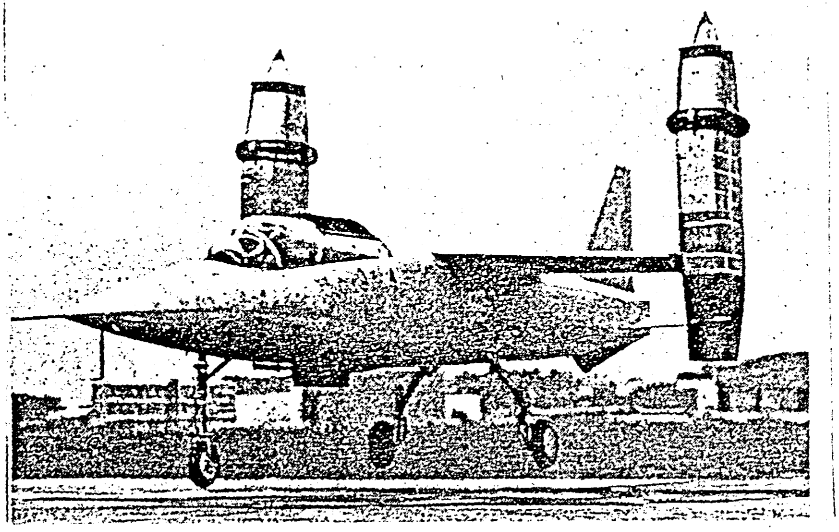
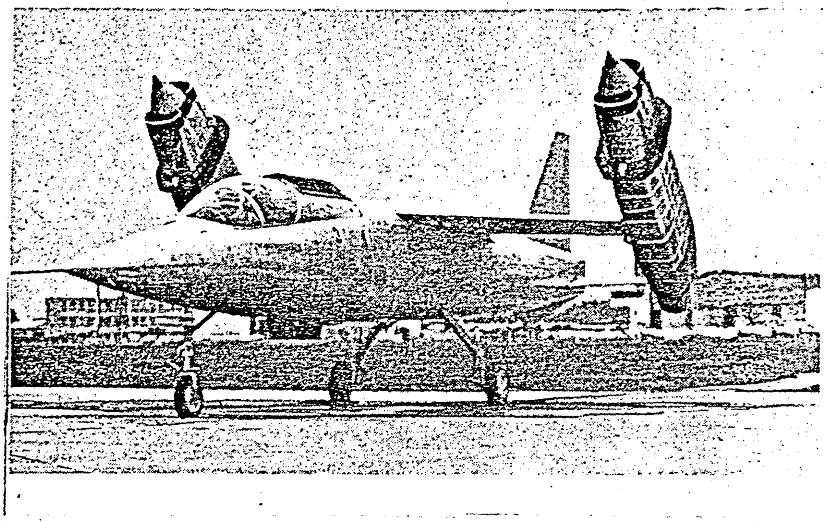


Fig 6: EWR VJ-101-C; six RB 145s



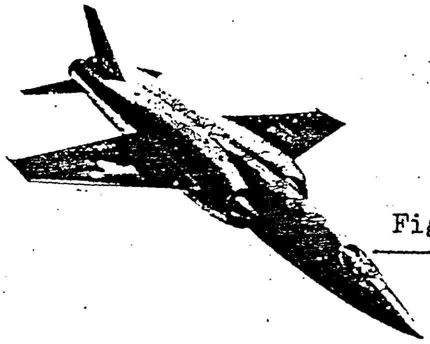


Fig 7: EWR VJ-101-D; four 162s and two RB/MAN 153s

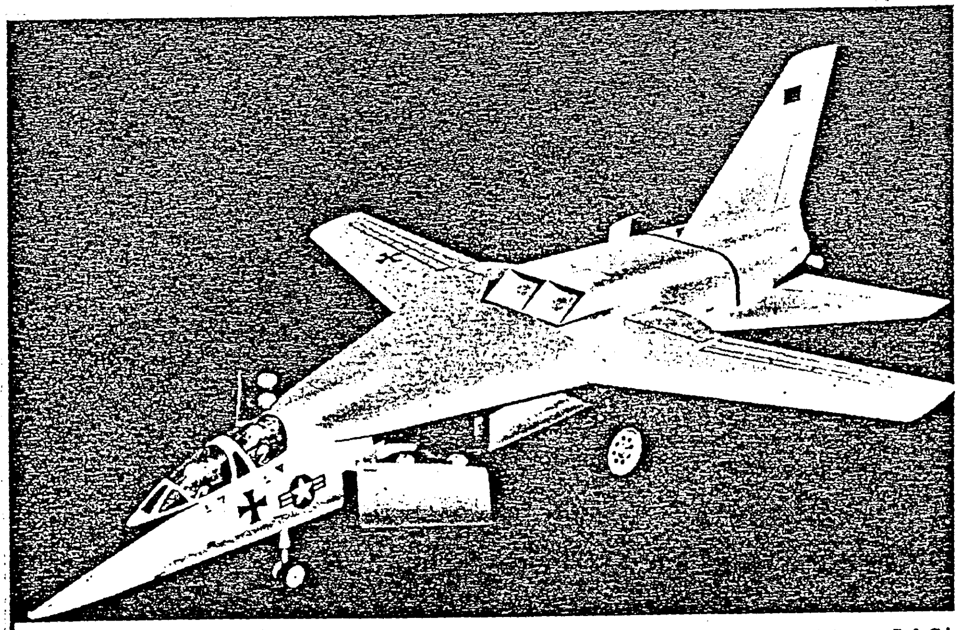


Fig 8: US/FRG project; note sideways-retracting lift-engines

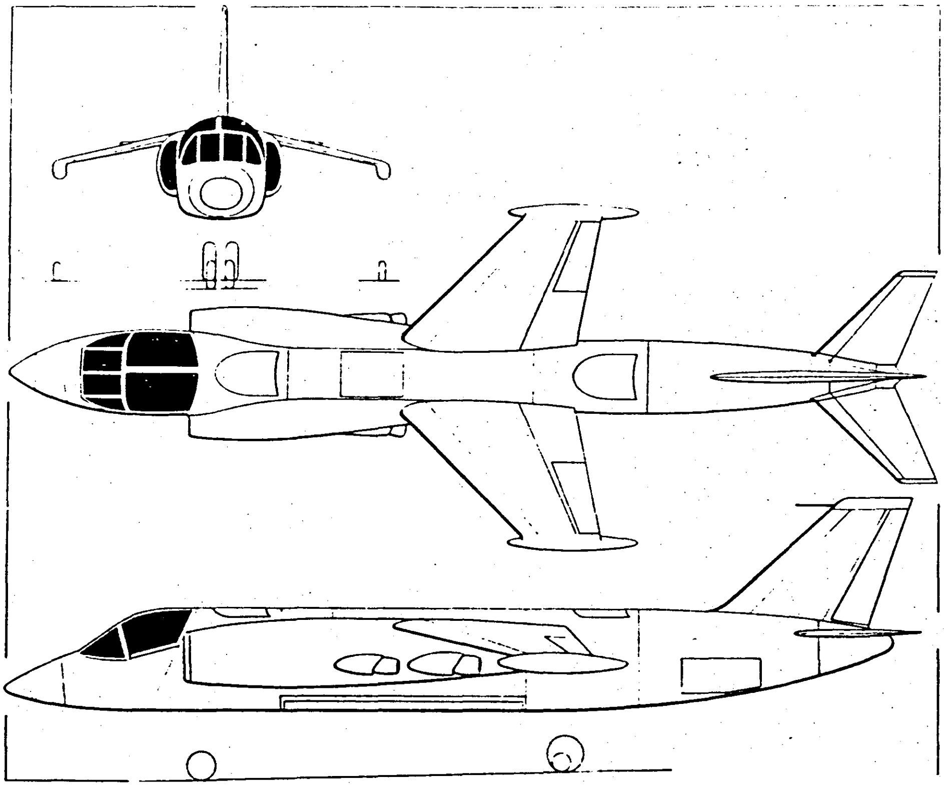


Fig 9: VFW VAK-191-B; two RB162s and one RB 193

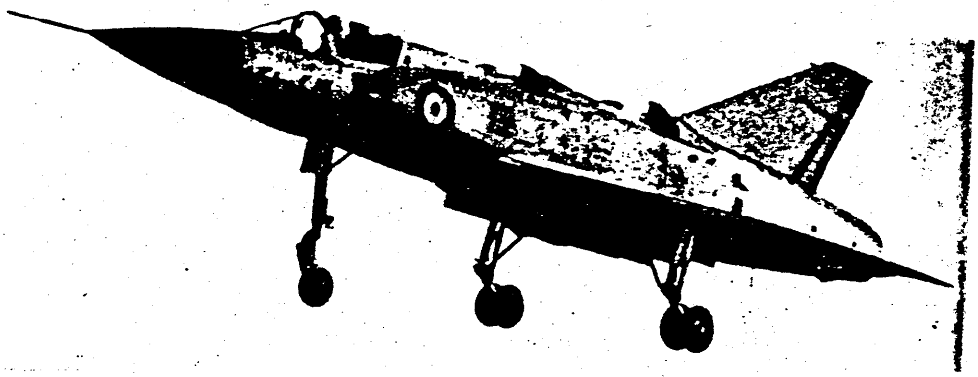


Fig 10: Dassault V-001 Balzac; eight RB 108s

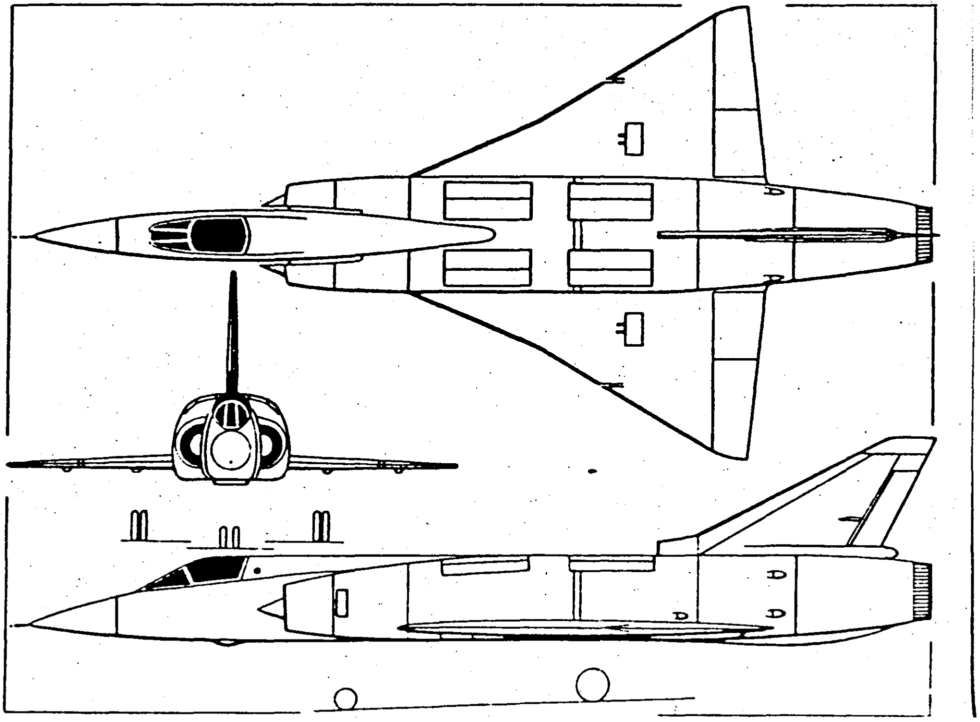


Fig 11: Dassault Mirage III V; eight RB 162s and one SNECMA TF 106

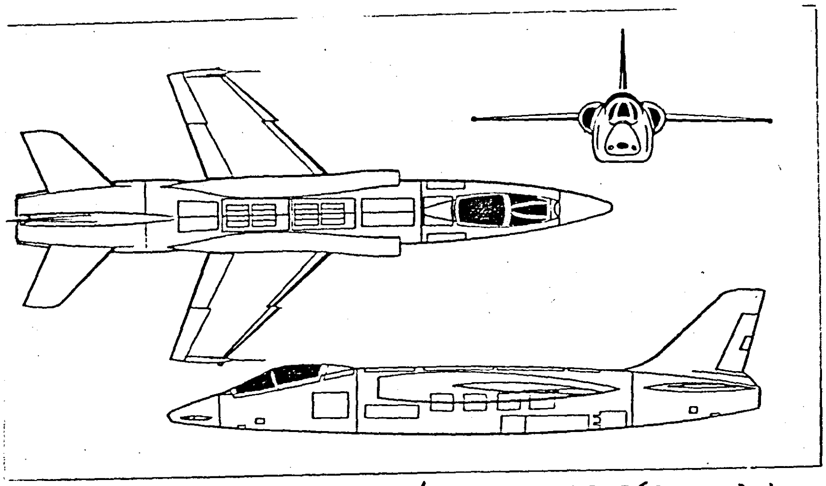


Fig 12: Fiat G 95/4; four RB 162s and two GE J85s

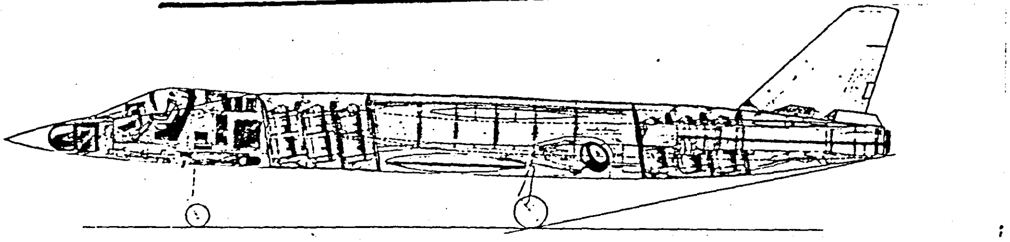


Fig 13: Fiat G 95/6; six RB 162s and two RB/MAN 153s

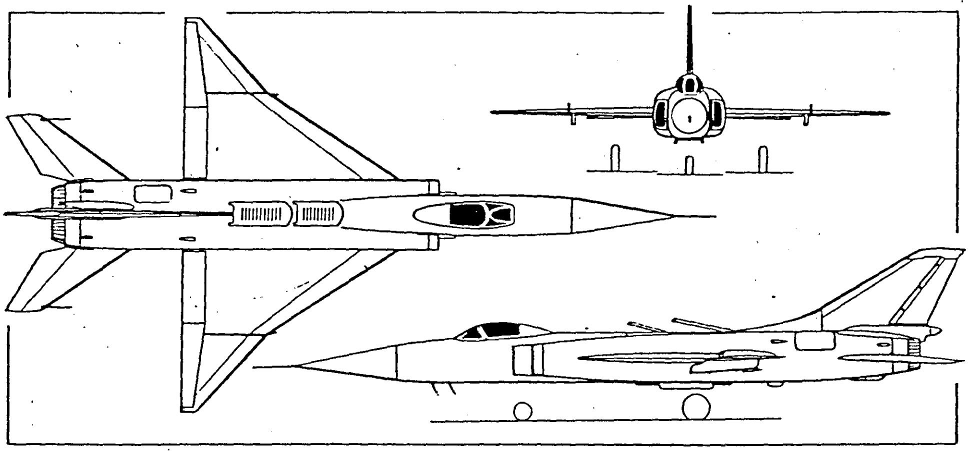
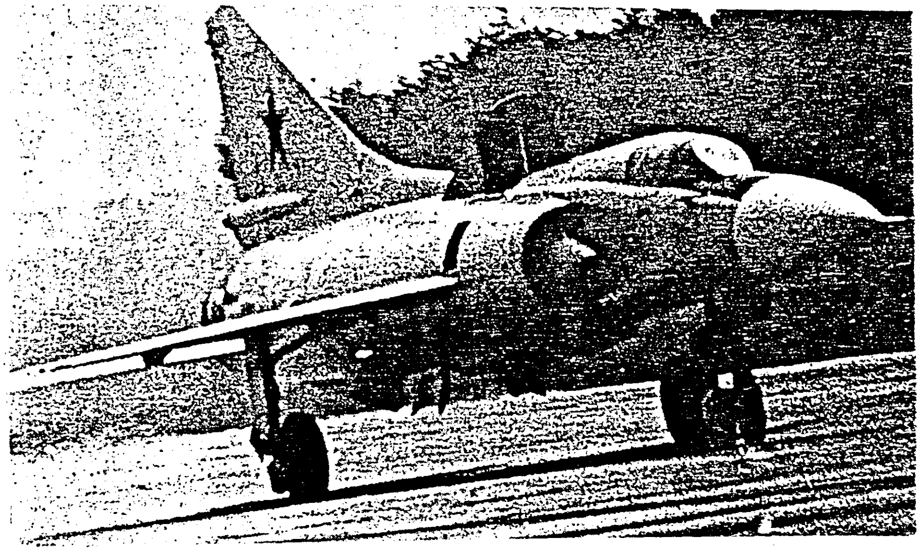


Fig 14: Mikoyan and Sukhoi STOL fighters; note lift-engine intake doors



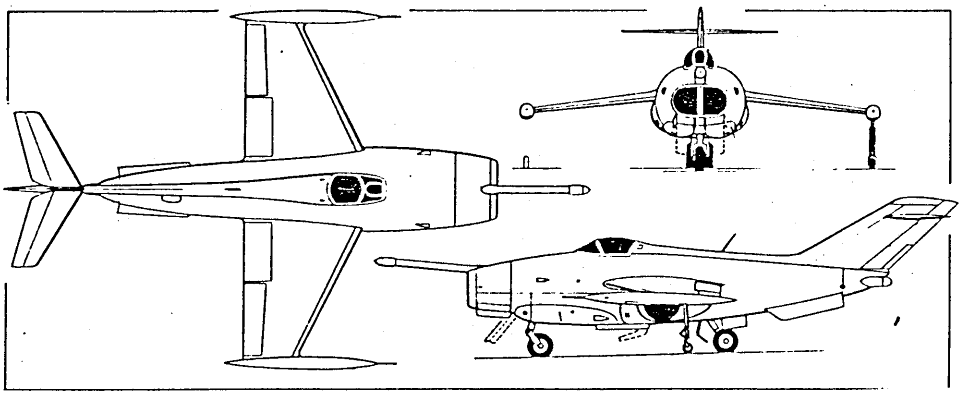
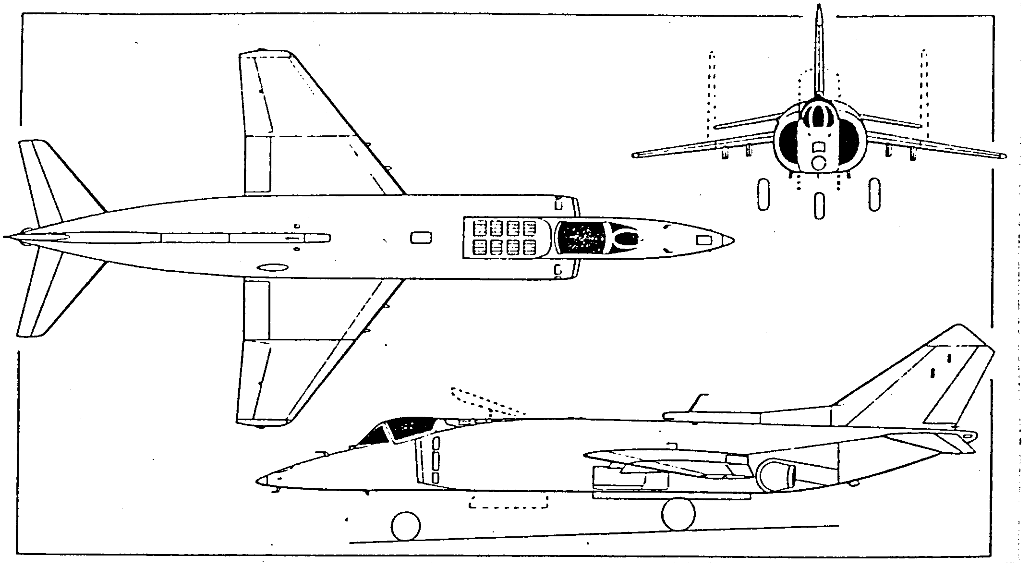


Fig 15: Yakoleb Freehand and YAK-36 Forger.



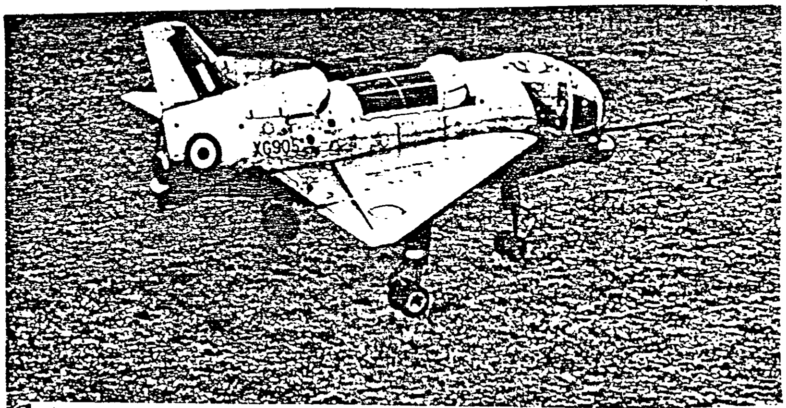


Fig 16: Short SC1

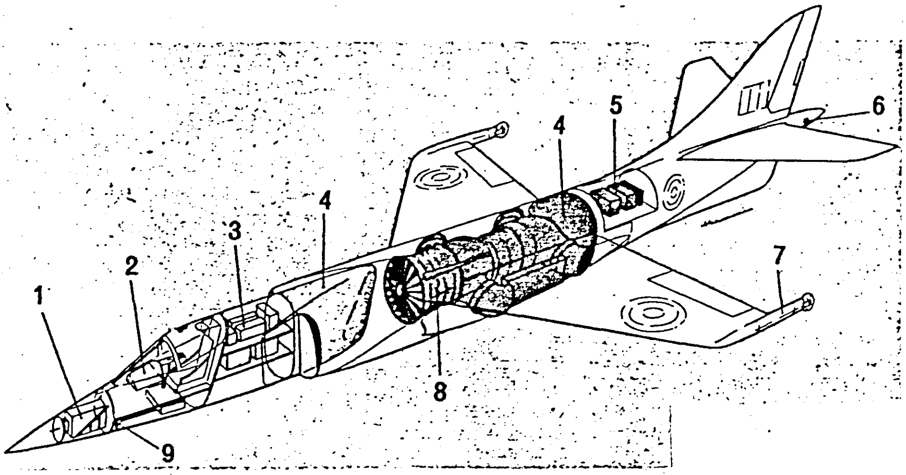


Fig 17: Hawker P1154

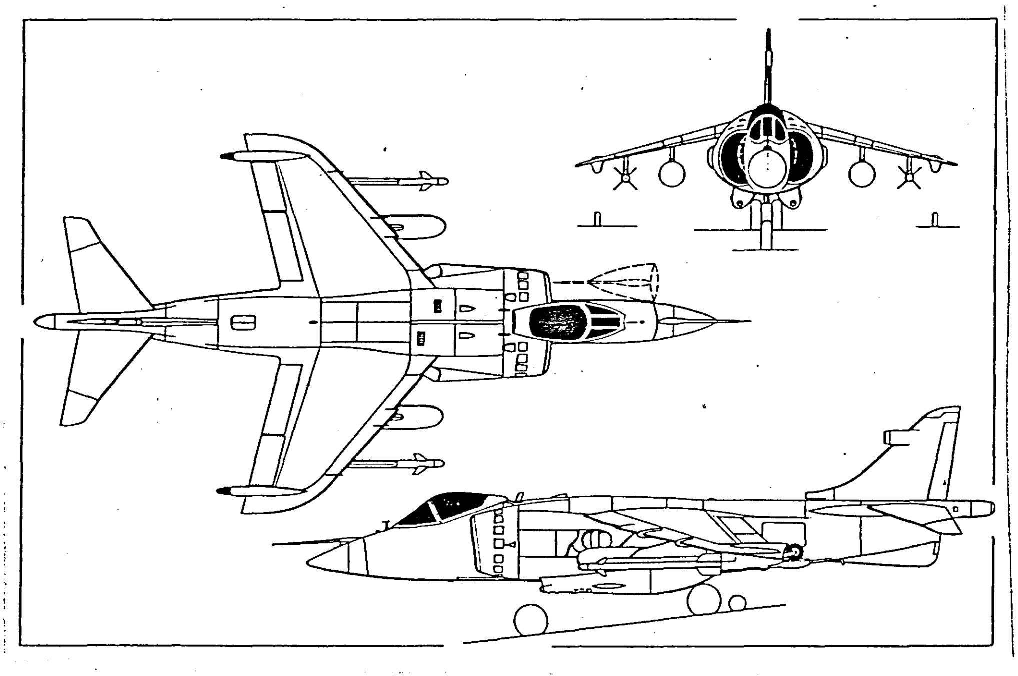


Fig 18: Sea Harrier

SECTION 5. THE PRESENT AND THE FUTURE

Section 1 finished with the contending V-STOL operators in the world's armed forces placed as follows:-

The USA. The United States Marine Corps has three operational squadrons of AV-8As and a further training squadron. The US Navy is looking into the future with its quest for aircraft to meet the requirements of V-STOL A, B and C, and the possibility that these together could bring to an end the era of the expensive super-carrier together with catapults, arrester gear and all the other trappings of Naval fixed wing aircraft operations of the mid-20th century.

The USSR. There are two Kuril class aircraft carriers at sea and a third known to be under construction. The Kiev and the Minsk both carry YAK-36 Forger VTOL fighters. As yet their mission has not been demonstrated but they are most likely intended as a counter to the anti-submarine aircraft of the western fleets. Two STOL aircraft with lift-jets have been demonstrated, but they do not appear to have been developed into anything more advanced for deployment in service.

The UK. The RAF has the Harrier Mk.3 established in squadron service. The Royal Navy looks to VTOL as its only means of keeping fixed-wing aircraft at sea.

What is the Latest State of Play?

L. The USA

The US Marine Corps, delighted with its vast experience with the AV-8A, seeks to buy the AV-8B, its linear successor, of which two prototypes, completed by conversion from AV-8As, now exist. The AV-8B can double the range/payload capacity of the AV-8A for the same engine thrust, it can deliver 3000 lbs of bombs half as far again as the A-4M for a third of the takeoff run, it can take 5000 lbs of bombs as far from a 900' run as the A-7 can from a 5600' run (Ref.1). They want it in service by 1984, and want to buy more than 300 copies.

The United States Defence Secretary is not so sure that it is a good idea. He cites their high accident rate with the AV-8A (29 out of 110) as evidence that VTOL is not completely proven in service, and is keen that they should take the A/F-18 instead, which would be far cheaper to buy for the USA and USMC together. The AV-8B project is still hanging on. The next stage after the conversion of the prototypes is to build four aircraft complete from new, and $108,000,000 has been released for Fiscal Year 1979 for the project to continue, partially reversing the decision to withhold the whole $203,000,000 required, which was made earlier on in the Defence debate.

The US Navy invited design studies for V-STOL A, a general purpose subsonic aircraft, and V-STOL B, a supersonic fighter. Numerous aircraft designs were submitted for both requirements (Ref.2), but preliminary studies of V-STOL A showed that the cost of the ASW version for instance would be one third higher per aircraft than that of a conventional design, and the development cost for V-STOL A and V-STOL B is likely to be at least $5,000,000,000 each (Ref.3). Also, it became apparent by the end of 1978 that existing aircraft types in service would not be able to hang on long enough for their V-STOL A successors to be developed and ready to relieve them at their posts. Time was pressing, and a gap in continuity could not be accepted. V-STOL A was abandoned (Ref.4).

But subsonic V-STOL has not been completely discarded and a relief is ready to fill the gap, at least to a limited degree. The US Cavalry in this case is played by an aircraft comprising the airframe and engine of the AV-8B together with the avionics being devised for the ground attack version of the F/A-18 Hornet. Designated the AV-8B Plus, this aircraft could operate from small aircraft carriers. (Ref.5). The sea control ship can be detected stirring in its sleep.

V-STOL B is still healthy, at least on paper. The aircraft types it is intended to replace are themselves barely yet established in service, so there need be no rush to make a firm commitment on designs for their successors.

The most interesting speculation in the V-STOL B activity is the renewal of interest in the tail-sitting Vertical Attitude Take-off Aircraft. Now that thrust/weight ratios of high performance aircraft can comfortably exceed unity, concepts like the old Ryan X-13 Vertijet are worth looking at again. This aircraft was controlled in the hover by means of a variable nozzle in the exhaust for effect on pitch and yaw plus reaction jets in the wingtips for roll. Trial reports show that it was controllable during vertical attitude takeoff, approach and hover, even in cross winds as high as 35 knots. Some control problems, due to engine gyroscopic couples and other unorthodox characteristics, did persist, but they were not insurmountable.

The scheme for sea-borne VATOL is to mount the aircraft on a grid pivoting over the side of the ship, launch it and recover it vertically, and rotate the grid to a horizontal attitude for aircraft handling. With a short flight deck, it could still perform short takeoffs in overload configurations. (Ref.6). It is claimed that VATOL would reduce susceptibility to exhaust gas ingestion or impingement on the airframe, and has no appreciable suck-down problem, while at sea the engines exhaust over the side so deck impingement presents no problem.

More research into high performance V-STOL aircraft was instigated in 1977 by NASA-Ames in conjunction with the David Taylor Naval Ship Research and Development Center. Four contractors, General Dynamics, Grunman, Northrop and Vought, were invited to submit designs for V-STOL B aircraft in two stages. The first stage was to plan the aircraft, and the second was to identify the aerodynamic uncertainties surrounding it and then define and plan a wind-tunnel and analysis programme to explore and resolve them (Ref.7).

The aircraft specification included a sustained Mach No. capability of 1.6, the ability to operate from ships wholly free of catapults and arrester gear, a VTOL weight of up to 35,000 lb, and the strength to sustain a load factor of 6.2 at M0.6 at 10,000 ft at 88% of this weight. Five designs emerged, three with Horizontal-Attitude takeoff and two Vertical-Attitude takeoff, and it is worth noting that for equal combat and mission performance the VATOL design weighed 11% less than the lift-plus lift-cruise designs. (As might be expected, the main aerodynamic unknowns were concerned with suckdowns and fountains on takeoffs and transitions, exhaust reingestion, nozzle and lift-engine contributions to drag, and the compromise to be made between reaction control system power and aerodynamic surface sizing). Two examples of designs submitted are at Figs. 2 and 3. Wind tunnel testing in support of the second stage of the design study should be under way now.

The eagerness of the US Navy, or at least some of it, to make a start on VTOL operations is shown by a suggestion in Interavia (May 1980) that they might purchase some Sea Harriers to try out as a stepping stone on the way to evaluation of a more advanced type of aircraft, as with the report in Flight (March 8, 1980) that the Chief of Naval Operations, Admiral Hayward, has made a proposal that the battleships Iowa, Wisconsin, New Jersey and Missouri be brought out of reserve to serve as vehicles for the AV 8B. This idea is supported by the US Marine Corps who favour fitting the Iowa with a hangar and skijump aft while retaining the 16" battery forward. (Aviation Week September 22, 1980).

Meanwhile, the XFV-12A is still "in need of a lift" (Ref.8) after being rolled out in August 1977, and a US Navy spokesman summing up V-STOL progress so far is recorded as ruefully remarking "The Air Force dabbled pretty heavily in V-STOL technology in the 60s before giving it up as a bad investment. They made sure they kept their distance when we took it up, and then sat around waiting for us to fall on our ass". (Ref.9).

More seriously, the US Under-Secretary of Defence for research and engineering says "We have either to greatly accelerate the programme and put it into system development, or we have to cut back very dramatically the amount of funds we are putting into it". In the latter case "That eliminates the requirements for V-STOL for another twenty-five or thirty years".

2. The USSR

No new VTO aircraft has been reported from the Russian front. The Forger has yet to be seen carrying a weapon load, so no speculation regarding the role it is intended to play can be confirmed. Undoubtedly there will be further fixed-wing aircraft to come, and future ships to carry them.

3. The United Kingdom

The Harrier GR Mk.3 is established in service with the Royal Air Force, and the Sea Harrier is now coming into service in the Royal Navy. HMS 'Invincible' is now in commission, HMS 'Hermes' is being converted for Sea Harrier use and two more ships of the Invincible class are on the way. All are or will be fitted with Skijump as the method óf launching their aircraft. The term Aircraft carrier is acceptable again.

4. Other Navies

Practical interest in VTO fixed-wing aircraft is now being shown by other Naval services. The Spanish Navy already operating Harriers from the 'Dedalo', are reported to have started building a light aircraft carrier in the 12000-14000 ton range capable of Harrier operation and the Italian Navy are building a Sea Control Ship, the 'Guiseppe Garibaldi' of a similar size and capability. Interest in these is currently being shown by the Royal Australian Navy in their search for a replacement for the 'Melbourne', and they are likely to select a VTO capable aircraft type with which to equip it. The Indian Navy have already ordered eight Sea Harriers to replace the Seahawks in the Vikrant.

The Aircraft

Steady progressive undramatic development has brought the Harrier cautiously but confidently along the path from P1127 to AV-8B. Its engine had advanced in output from 13,500 lb thrust to 21,500 lb thrust with 24,500 lb known to be capable of achievement. Inevitably there is a UK Harrier successor on the cards, and it is now public knowledge (Ref.11), that Air Staff Target 403 for the Harrier/Jaguar successor has now split into two aircraft, of which one is the so-called Super Harrier, the big-wing Harrier Mk.5. It is also known (Ref.12) that testing has been resumed on the Plenum Chamber Burning enhancement of the output for engines like the BS 100 which was shelved in the 1960s when the P1154 was cancelled.

So the Harrier family has an assured future with both the Royal Air Force and the Royal Navy. In the Royal Air Force it can carry on where the current Harrier leaves off, in the Royal Navy it starts with a clean sheet and the unique opportunity to sire a whole new generation of Naval aviation.

Other users of the Harrier have been able, if they so choose, to operate in the STOVL mode, that is they have used a rolling takeoff to get it airborne while it is heavy, too heavy for a straight vertical takeoff, and have recovered it vertically, if they wished, when its overload has been burned off.

This option will be open to the Royal Navy only where a deck run, maybe with a skijump, is available. This will offer employment to the majority of our purchase of four dozen or so Sea Harriers but not to all. The real challenge is to provide enough decks for as many as can be made available, and to do this we must look into ways of achieving vertical takeoff at higher maximum weights. Discussion of these problems forms the substance of the next part of this study.

The Harrier at Sea

Ref (10) sees roles for the aircraft as follows:

1. Fighter/Intercept Patrol, with potential targets being large subsonic patrol aircraft and "other fighter/attack aircraft". It has to be accepted that there are other fighters/attack aircraft still for which the Sea Harrier is no match at all.

2. Reconnaissance

3. Strike, especially anti-ship, (once the air-to-surface missile fit has been decided)

4. Close Air Support. This is not seen as a prime role for the Sea Harrier at present, but it is one in which the aircraft type has acquitted itself very well in other Services. It is impossible to over-estimate the boost to morale the Infantryman gets when he is covered by friendly aircraft joining in his own particular corner of the fight.

5. Anti-submarine

6. Defence/Offence in Port

Consideration of the above shows that the aircraft has no set role at all, it is not the direct replacement for any other aircraft, it is a step backwards in performance from its predecessors. This is no bad thing. The Harrier itself is not the next advance in a line of fighting aircraft, nor was it the aircraft the RAF wanted when it was ordered as a substitute for the cancelled P1154, in fact it very nearly never came into existence at all. But once it did get into Service, roles were found for it which became essential and unique, so much so that both the USAIC and the RAF now demand that its successors must display the same V-STOL versatility.

It is not the business of this paper to argue tactics or policy, but it does seem reasonable to draw a parallel to what has gone before, and so deduce that the sooner we learn to operate the VTOL aircraft from a small deck, the sooner we will convince ourselves, and others, that there is indeed a place for it in our armoury, and that we ought to have done it years ago.

FIGURES

SECTION 5

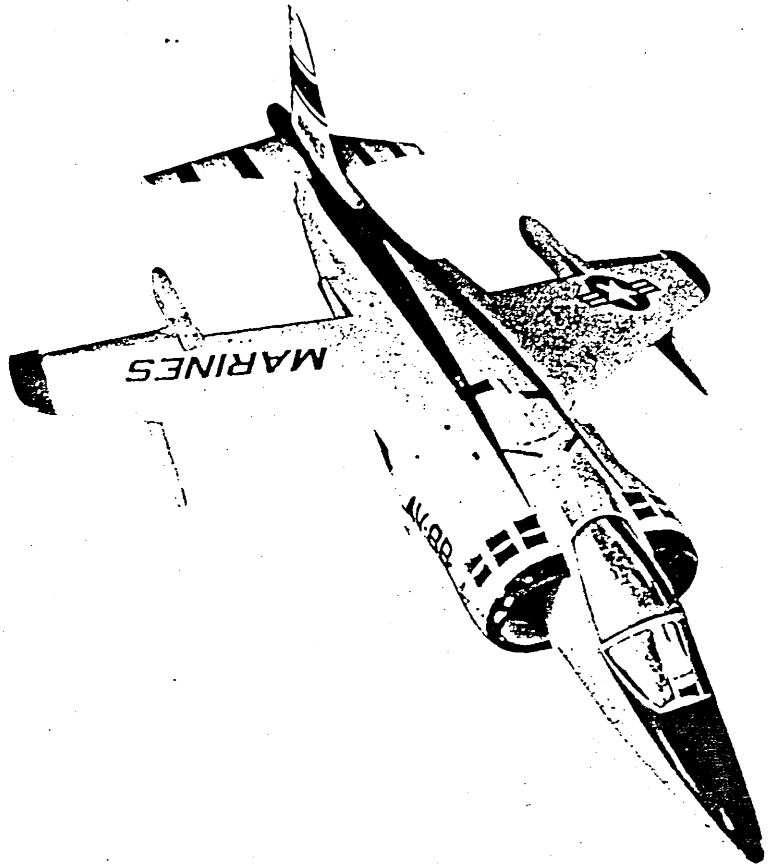
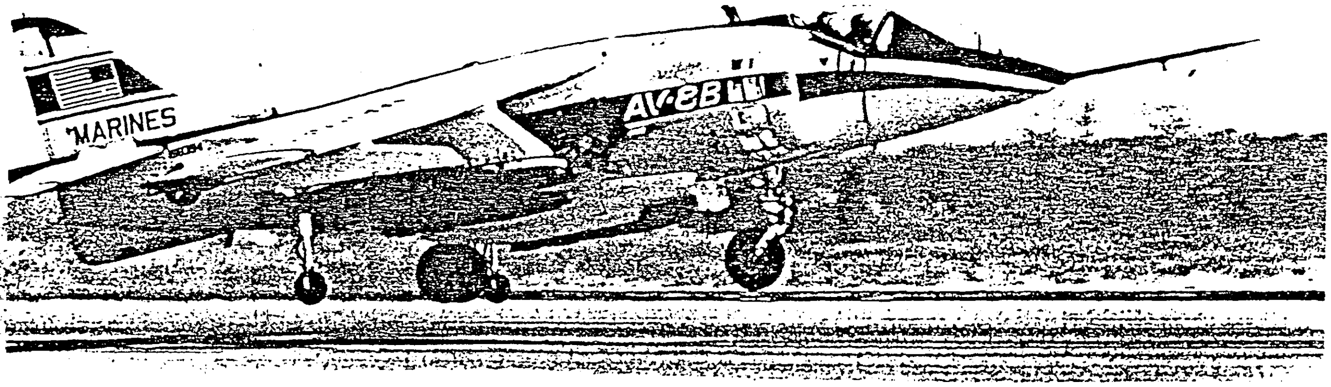


Fig 1: US Marine Corps AV-8B



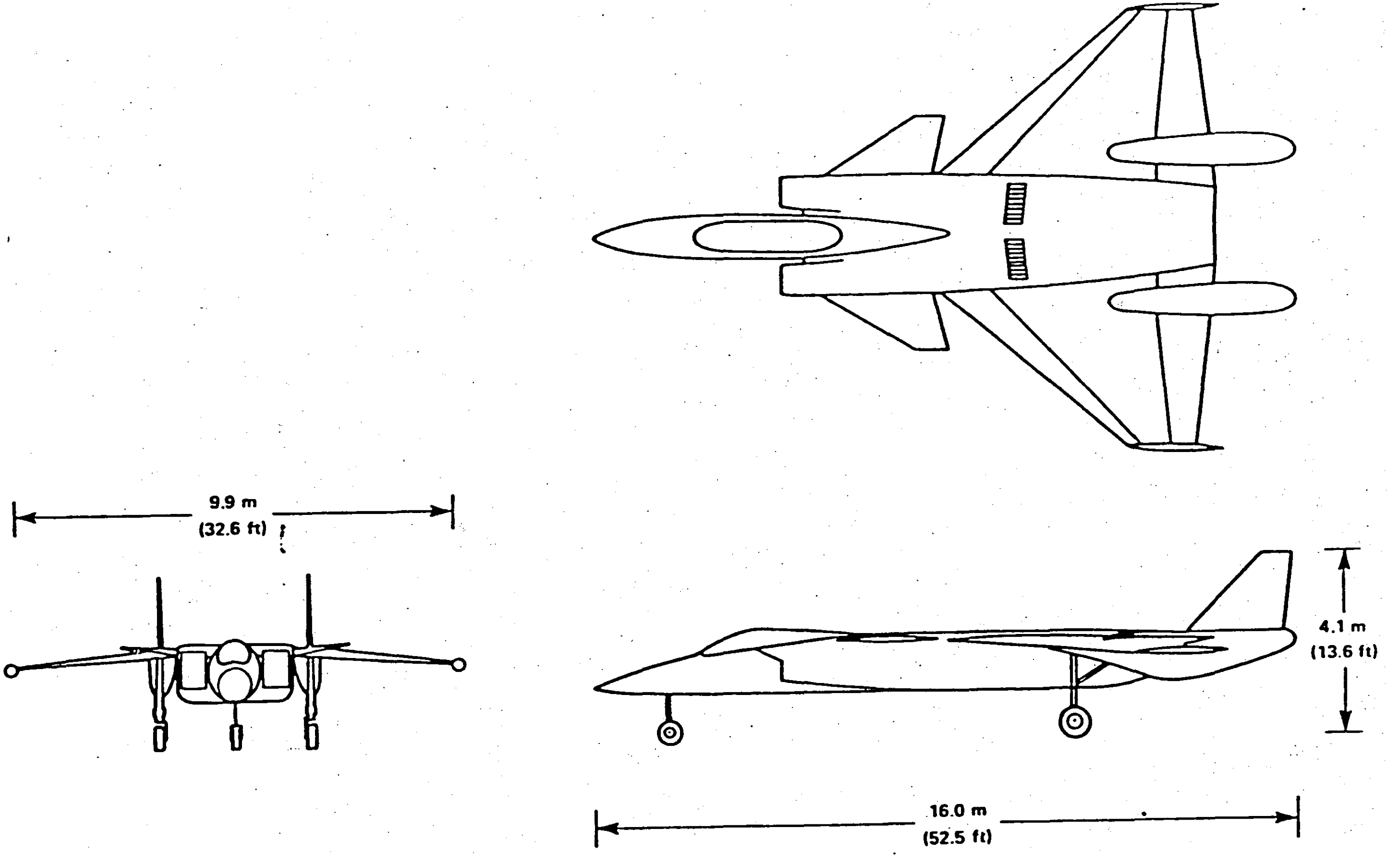


Fig 2: Northrop HATOL submission

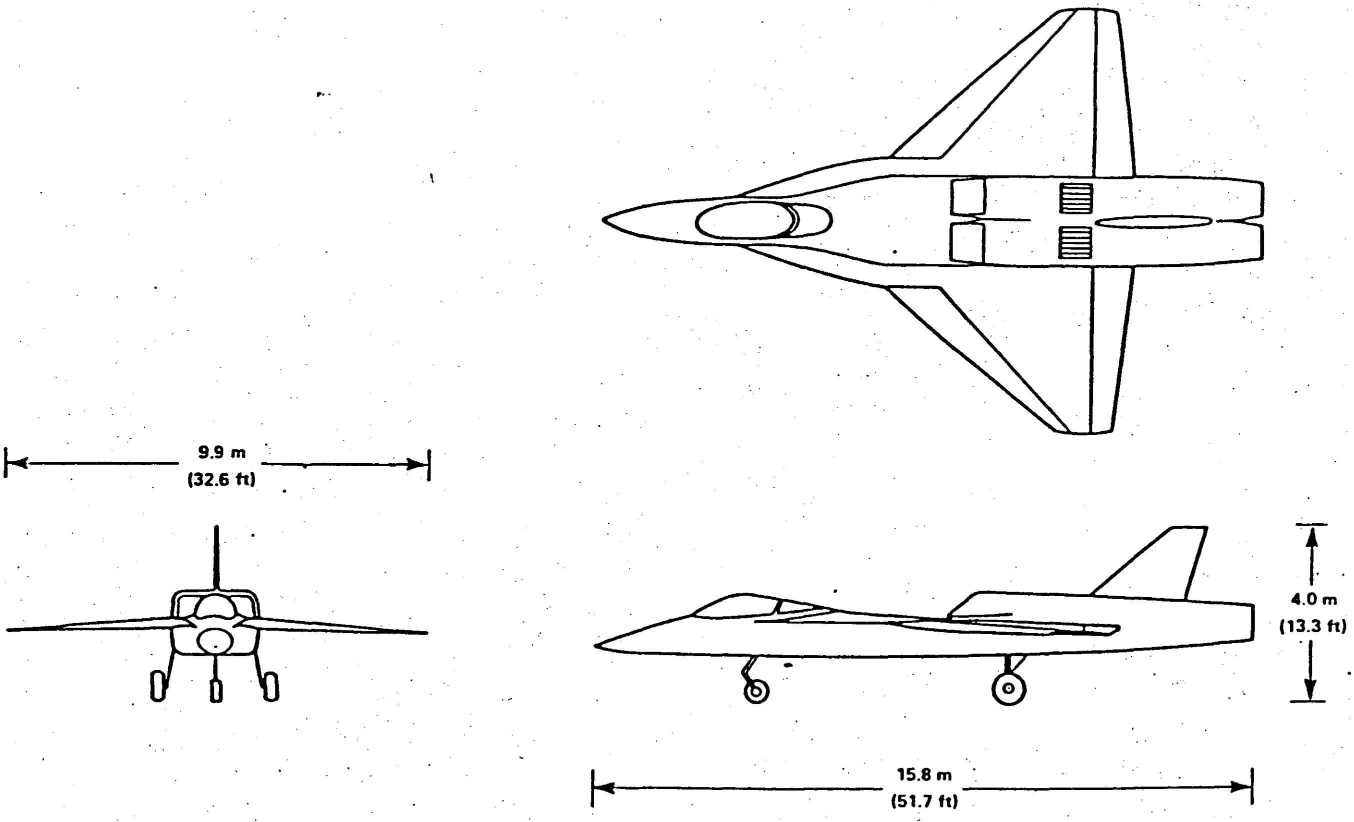


Fig 3: Northrop VATOL submission

SECTION 6. LAUNCH METHODS, AVAILABILITY, SUPPORT AND RECOVERY OF THE CURRENT AIRCRAFT AND ITS POSSIBLE SUCCESSOR

The material in Volume 2 of this study bears a security classification and so is not available for consultation from an open shelf. However, for the sake of completeness,and to round off Volume 1, its substance and conclusions are summarised to form this final section.

The reason for the higher security classification lies for the most part in the values of the parameters discussed rather than in the existence and nature of the material, equipments and techniques introduced, and so very little of the subject matter itself is omitted. In the summaries which follow, figures for attributes such as performance, reliability, dimensions and weights are generalised or omitted. The conclusions, where they are based on comparisons such as orders of merit, remain unaltered.

Launch Methods

The possible means of launching a VSTOL or STVOL jet aircraft may be listed as follows:

Free takeoff	Direct vertical takeoff Horizontal takeoff Takeoff from an inclined ramp (i.e.skijump)
Assisted takeoff	Takeoff with rocket assistance along the deck and/or in flight. Takeoff with catapult assistance

They are considered in detail in Parts 2 and 3, of which a summary follows.

Free takeoff

Direct vertical takeoff. In order to take off vertically an aircraft must have the following properties:

It must develop a thrust that is comfortably greater than its takeoff weight. The margin must be big enough to allow for thrust losses due to suck-down effects and exhaust recirculation, for the generation of flying control power, and for the upwards acceleration to be clean and positive. The thrust must be capable of being directed downwards, either by swivelling the exhaust(s), or by tilting the entire aircraft.

The demands made on the tolerance of the aircraft's propulsion and control system and integrity will be greater for vertical takeoff than for any other method of getting airborne. At takeoff the aircraft is at the limits of its performance at the very time it is at its most vulnerable to a malfunction, and a failure at this stage is almost certain to lead to the loss of the aircraft or at least very heavy damage. For the pilot's survival his ejection seat will have to be able to work successfully from a free-falling aircraft with no contributory slipstream to assist the escape.

Vertical takeoff from the deck of a ship causes a major disturbance all around the aircraft, and if some form of reheat is employed, is liable to damage the deck surface also. The problem can be alleviated a little, in theory at any rate, by shaping the deck so that the jet efflux is channelled away to exhaust over the side of the ship, by, for instance, use of a gridded surface. This would offer the benefit too of reducing the loss of lift due to recirculation of hot gases. The disadvantage would be the loss of ship space below the nominal deck level. In a small ship this consideration would make such a development unacceptable.

Some lift can be recovered by shaping the underside of the aircraft in such a way as to trap some of the jet efflux as a form of ground cushion. This is done in aircraft of the AV-8B family using CADs (Cushion Augmentation Devices). These take the form of a cross-dam attached to the nosewheel leg, and longitudinal strakes on the gun pods. Their advantages are apparent of course not only on takeoff but also on landing.

If the aircraft develops no lift from anything other than its engine, then its payload is bound to be lower than if aerodynamic lift were available as well. So direct vertical takeoff is the least efficient means of getting airborne. Its only saving grace is that it takes up the smallest amount of deck.

Horizontal takeoff

If the aircraft is allowed a takeoff run before getting airborne and it gets going fast enough for some of its weight to be carried by its lifting surfaces, then obviously it will be able to launch at a weight higher than if it were taking off vertically. The price to be paid is that deck space must be set aside for the takeoff run, there may be a problem with the cliff-edge effect as the aircraft leaves the deck, and if the ship is pitching it is desirable that the aircraft depart on the upswing not the downswing. This was fairly east to arrange for a flat-deck catapult launch which was swift and short enough for the Flight Deck Officer to be able to time its initiation correctly, but is much more difficult for a pilot-initiated free takeoff. All the same, early STOVL operations at sea were exercised from a flat deck, and flat-deck performance figures continue to be published for the aircraft in current service.

Takeoff from a inclined ramp

This is the launch method now in service in the Royal Navy, the ramp being colloquially known as a ski-jump. The theory is described in Part 2, where a mathematical model of the launch dynamics is developed and validated against results obtained by more exhaustive means. The model is exercised over a range of takeoff angles and jet nozzle angles to be selected post-launch in a search for the most beneficial combination. The sensitivity of the launch performance to variations in wind strength, ship pitch and engine thrust is also explored.

It can be shown that while in theory the best results would be achieved by launching from a ramp inclined at 20° - 30°, the actual values for practical application are limited by ship and aircraft structural considerations to about 15°. The takeoff distance can be minimised by using a deck hold-back mechanism to allow the engine to develop its full thrust potential before the aircraft starts to move. While the ski-jump's most likely application is to aircraft with vectored-thrust engines, it is theoretically possible to gain similar advantages by vectoring the aircraft itself, so long as it can achieve and remain controllable at a high angle of attack. Thus the F-18, for example, is theoretically a potential ski-jump aircraft.

Assisted Takeoff

The improvement in takeoff weight obtainable from a skijump launch can of course be realised regardless of how the aircraft is propelled up the ramp, or how it may be assisted during the ballistic phase of its flight after launch. Methods of assisting takeoff are looked at on the assumption that the launch they are assisting is to be from an inclined ramp. (Horizontal launching after all may be regarded as a particular case of ramp launching in which the ramp angle of inclination is 0°).

Rocket assistance. An aircraft which is going to be able to land vertically on a deck at the end of its sortie will have an impressively high Thrust/Weight ratio even at takeoff. If its brief takeoff run is to be assisted significantly by some form of rocket motor, then the output of this motor (and hence its bulk also) would have to be formidable indeed. Study of the size of the rocket motor installation that would make a noticeable improvement to the unaided takeoff performance leads to the conclusion that rocket assistance in this application is not practicable.

Rocket assistance in flight is, however, another matter, not if it is to be used to speed the aircraft along its flight path, but rather if it is to help support the weight of the aircraft during the semi-ballistic phase. That at least is the theory. Unfortunately, study of the practical applications of such a scheme shows that several physical considerations intervene between theory and realisation. First there is the problem of locating a rocket motor in the aircraft so that its line of thrust has a major upwards component through the centre of gravity. This means siting is somewhere amongst the undercarriage. Then there is the question of justifying such an installation when it is not likely to be used for every flight. Then the burn period of the rocket motor must start and stop at precisely the right times. All these points lead to the conclusion that rocket assistance for S/VTO flight need not be pursued any further.

Catapult assistance. The energy needed to accelerate an aircraft with the operating weight of the Harrier family up to the relatively low speed necessary for a ski-jump takeoff is but a small fraction of that developed by the catapults in current aircraft carrier service. This means that such a launch could be achieved by a light-weight catapult, and this proposition is, initially, an attractive one to consider.

A light-weight low-energy catapult suitable for the purpose could be powered by either compressed air or by chemical energy in some form, direct, as in a cordite catapult, or indirect if the energy developed were stored and then released using the medium of a flywheel. In each instance the system considered has the attraction of being self-contained. In Part 3 all these types of launcher are discussed in detail. When considered as part of a system all three share the same disadvantages. These are that the aircraft would have to be specially configured to suit them, and that the relatively low utilisation that would be expected of them could never justify their installation in a space-conscious ship of the size being considered in this study.

Conclusion

The conclusion reached is the vectored-thrust aircraft of this generation intended for operations from a sub-capital ship would get airborne entirely by its own efforts, either vertically or preferably, from an inclined ramp. It is shown that a flying-off deck of about 250ft in length and incorporating a ski-jump can match the gain in launch performance that could be conferred by either rocket or catapult assistance. Aircraft of any succeeding generation will be launched the same way, and should be designed with suitability for operational ski-jump operation as an essential design factor.

Availability

Availability in the context of aircraft operations is an easy term to play with but a difficult one to pin down. For it to be discussed to any purpose its definition must be agreed, and the way it is measured must be consistent and free from ambiguity. This is a requirement which has still to be realised in current experience. Before Availability can itself be forecast, a forecast must be made of Reliability and Maintainability, (both of which have to be pinned down and measured in their turn), and in addition the flying programme or duty cycle to which the Availability measure is intended to refer must be defined. Failure on the part of Defence Staffs on both sides of the Atlantic to grasp the significance of this latter point continues to lead to misguided discussion of figures for "Availability" which are at least spurious and at worst potentially damaging.

The terms of Reference of this study require that an assessment be made of the Availability to be expected from an aircraft detachment to a small ship. In Part 4 the sequence in which this problem is approached is as follows. First the standard measures of Availability are described. For a measure to be of real (as distinct from spurious) application it must be as reliable when used to forecast Availability as it is when recording it. So a series of simulations of a day's flying programme is run for a range of values of the variables concerned. Mean Time between Defects and Sortie length combining as a measure of Reliability, and Mean Time to Repair and Time between sorties combining as a measure of Maintainability. The intensity of the flying programme itself is varied as well. The outcome of the day's simulation is a measure of what the day's likely achievement would have been in terms of task accomplished compared with task demanded. This result is compared with what each definition of Availability would have forecast.

The findings of this stage were that the standard measure of Availability (Mean Time between Defects divided by (Mean Time between Defects plus Mean Time to Repair)) is useless in this application. Far better is one sometimes called Operational Readiness. This is defined here as:

$$P_{or} = R(t) + Q(t) \times P(t \text{ maint.} < t \text{ next launch})$$

or in words "Operational Readiness is the sum of the probabilities that the aircraft is serviceable now, and that it is not serviceable now but will be serviceable in time to meet its next call".

The next step is to seek representative values of the parameters in use for the aircraft type being considered, and to see how they influence the simulation results. The outcomes are that while a single aircraft could give a reasonable account of itself for a short period, much better results would come from a flight of three. These could sustain a continuous ripple flying programme to a high degree of probability for a useful length of time - depending on certain limits of Reliability and Maintainability not being overstepped. For the best flying success rates to be achieved the Mean Time between Defects must not be less than a stated value, and the Mean Time to Repair must never be greater than another stated value, while the programme itself must take account of these.

The first, Mean Time between Defects, is largely a fundamental characteristic of the aircraft itself and post-design efforts on the part of operational management is unlikely to change it much, but the second, Mean Time to Repair, while also a characteristic of the aircraft, can be influenced by the operational management to a high degree. It is no use having the aircraft designed to be maintainable if the maintenance activity allows delays to inflate the repair time (due to lack of spares, test equipment, tardiness in arranging aircraft movements to servicing positions etc). In availability achievement, MTTR is a driving parameter; let it get slack and availability is lost.

Those lessons must be applied very early in the gestation period of the next aircraft. Its targets for Reliability and Maintainability must be set advisedly, and must be regarded as being just as necessary to achieve as are those for performance and other physical characteristics. It must be recognised too that speed of rectification in the ship is another vital component of the availability package.

Support

In Part 4 it is shown that a vital factor in keeping the aircraft available is the speed of rectification of defects. A value is put on this which in turn can be used to weight the constituents of the support echelon of manpower, spares and servicing facilities. Part 5 describes how the most effective support activity can be designed at the lowest cost and explains the compromises which have to be made. At a less demanding level it quantifies the range of consumables (fuel, water, weapons) that a detachment would need.

It is shown that while a detachment of a single aircraft could sustain an acceptable level of availability for a reasonable time, the scale of the support activity required to bring this about would be disproportionately high for the return achieved. For example the bulk of Ground Servicing Equipment necessary for a flight of three aircraft is only about one third greater than that needed to support a singleton, and it is eventually concluded that operation of a single unit would not be worthwhile as a regular exercise.

Operation of a flight of three could be kept going economically for quite some time. Eventually, though, a stage would be reached where a maintenance activity would be required at a level which it would not be cost-effective to provide at any location other than a capital ship or parenting air station. Deciding on the cut-off level at which this stage is reached is a matter of balancing the associated probabilities, on the one hand, say, that an engine change will be necessary, on the other that an engine change facility will be established and then not used.

A big problem to be faced in planning a small-ship detachment is that of finding adequate stowage for weapons and other disposable gear. Planning must be done, presumably, with the expectation that each aircraft must be able to fight on every sortie. This means that each aircraft must be provisioned with at least two missiles and two drop tanks for every trip, so even one days' intensive exercise without underway replenishment would consume an alarmingly large bulk of equipment, all of which has to be stored somewhere.

Ship Considerations

In Parts 2 and 3 it has been shown that the vessel to carry a detachment of STOVL aircraft should have a flying-off deck some 250ft in length. Part 4 has concluded that the airgroup should be at least three aircraft strong, while Part 5 has put a figure to the size of the support facility required to keep it going. The next input to the specification is the consideration of what weather and sea state the airgroup should be able to operate in. Study at sea and weather records for the North Atlantic Station, together with an elementary look at ship motion theory, combines with all the other requirements to point to a displacement ship of some 400ft waterline. This could be a Small Waterplane Area Twin Hull (SWATH) ship, an adapted merchantman or, more realistically, a ski-jump-carrying version of a current advanced frigate of about 6000 tons. If these requirements are met, the question of what size of deck is necessary for landing is taken care of, as it is shown that unassisted vertical landing will be the only way to recover, and the space necessary fits within the boundaries of the flying-off deck.

More exotic vessels, i.e. hovercraft and hydrofoils, are considered for this role but rejected. The philosophy behind the rejection is that these are high speed vessels, and the reason for their call for high speed is that the weapons they are intended to deliver are relatively slow, being, in the limit, either infantry or ASW helicopters. If, as in this case, the weapon is about twenty times faster than the ship, then doubling the speed of the ship does not advance the effectiveness of the weapon in the same proportion. The practicalities behind the rejection are first, that the speed advantage these vessels have over a surface displacement ship is gained at the expense of efficiency (Thrust/Weight ratios of about 1:15 compared with 1:100 for a ship), and second, that even the largest one yet planned is at 3000 tons still not large enough to mount the airgroup required.

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THE EMPLOYMENT OF JET VSTOL AIRCRAFT AT SEA

PART 2

VARIATIONS ON THE SKIJUMP

SUMMARY

The Taylor study was worked on the basis of the aircraft completing its transition to wing-borne flight at the end of a ballistic trajectory when it had returned to the level at which it was launched. In this paper the flight path is reworked to give a set of conditions such that wing-borne flight is achieved by the top of the trajectory.

First the flight of an aircraft with jets deflected is investigated for a range of weights, launch speeds, launch angles and jet deflections, both fixed and variable, in a search for a pointer to the best set of launch conditions. Using the equations of motion derived and employed in the Taylor thesis an elementary program is used to derive the relationships between launch angle and speed achieved at the peak of the trajectory, first with the jet deflection fixed relative to the aircraft and then with it fixed relative to the horizon. This latter is a preliminary study of whether scheduling the jet angle in flight might lead to a worthwhile gain in performance, and is followed by a further variation in which the 'Down' selection is made at varying times after the instant of launch.

Then the program in use is further amended so as to give a value of launch speed producing a safe condition at flyaway, 'safe' being arbitrarily defined here as wing-borne flight from a trajectory where the vertical velocity upwards is never less than 5ft/sec. The gain made possible by varying the launch condition and techniques can then be assessed in comparison with the absolute launch parameters required. The amount of sensitivity to variations in wind strength over the deck and in engine thrust can also be looked at. These variations in performance can then be set against the potential gains offered by adjusting the launch conditions to see if these are worth attempting to harvest.

The method of analysis used is a very simple one, and it takes no account of secondary effects such as jet-induced lift losses or gains, variations in wing flap settings and the like. All the same its validity is affirmed by comparing the results it obtains with performance figures obtained by more exhaustive means.

No sites of possible break-throughs in this field have been espied. What has been achieved however is the production of an introduction to the workings of a ski-jump whose results are applicable to the Sea Harrier and whose methods could be applied to any future aircraft wholly or partially propelled by vectored thrust.

'I can't believe that,' said Alice.

'Can't you?' the Queen said in a pitying tone. 'Try again, draw a long breath and shut your eyes.'

Alice laughed. "There's no use trying,' she said: 'One can't believe impossible things.

'I dare say you haven't had much practice,' said the Queen.

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APPENDICES:

INTRODUCTION

This paper follows one titled "VSTOL, THE STATE OF THE ART, SUMMER 1979" which was produced as a preliminary to a Ministry of Defence (Navy) study on the possible application of the techniques of VSTOL to sub-capital ships of the Royal Navy.

The first part of the task was to explore the possible role of VSTOL aircraft in such ships, and indeed explore the role of VSTOL in a Royal Navy of the future. The next is to investigate how launch weights higher than those possible in pure vertical takeoff may be achieved, with especial reference to the employment of the ballistic launch technique which is meeting with such success under the popular description of skijump.

This paper describes that investigation.

In aviation history, no less than in all history, it is the firsts who are always remembered. Everybody knows the name of the first pioneer to cross the English Channel in a heavier-than-air machine, everybody can recall the names of the pilot and navigator of the first aircraft to complete a non-stop flight across the North Atlantic (even if they are unsure of which was which); all Americans can name the pilot who was first to complete a trans-atlantic solo flight. But very few people have ever bothered to find out who was the second aviator to emulate these achievements, fewer still know or care who was the eighth or ninth, or twenty-ninth for that matter, even though these individuals probably found the task before them no less daunting than did the first.

It is in the role of the twenty-ninth (or there abouts) individual to explore the possibilities of the Skijump launch that this writer sets about his appointed task.

Six years ago, Lieutenant-Commander Douglas Taylor, Royal Navy, presented a thesis with the title "The operation of VTOL aircraft from confined spaces" (Ref.1).

In the short term this Thesis was to gain the award of a Master of Philosophy Degree from the University of Southampton, in the longer term it won him universal acclaim throughout the aviation world as the inventor of the skijump.

Taylors idea for exploiting the potential of ballistic-flight below the stall had been accepted by the Ministry of Defence as being worth looking into further even before his year at Southampton. Once it was completed it still had a very long path ahead of it before it was in a position to produce any practical results.

Following publication it had to be fully reappraised by the experts. First it was evaluated by the staff of the Flight Systems division of the Royal Aircraft Establishment, Bedford, then it was studied all over again by Hawker Siddley Aviation, the manufacturers of the Harrier, the aircraft for which it was devised. They were awarded a development contract to evaluate the skijump most thoroughly and then to design and build a skijump ramp from which their aircraft could fly and demonstrate that the theory really would work.

In transit through these many series of expert hands and across so many expert minds, the content of Taylors original work was refined and rearranged practically beyond all recognition. All the second-order considerations he had chosen to set aside now had to be reintroduced his mathematics, (which I am sure he would not object to seeing described as being workmanlike rather than elegant), had to be purified and computerised, safety factors and scatter factors had to be brought into the main stream in order to convert the perfect average aeroplane of theory into the imperfect safe aeroplane of practice, his whole ballistic theory was reappraised and half of it discarded. By the time the first Harrier curved into the air from the exit of the prototype skijump at Bedford in the Autumn of 1977 all that remained of the original Southampton thesis was the brilliant idea at its core. Theory had now been engineered into practice.

THE BALLISTIC LAUNCH

Some Figures for thought

At the time of writing, the operating Data Manual for the Sea Harrier, ie that volume which will set out details of weights, thrusts, settings and limitations for the Sea Harrier, has yet to be produced. For this reason (and also in order to keep the security grading of this paper safely at a level below Confidential), numerical values of Harrier performance and of other measures used are those used in the original Thesis (Ref.1) in which the ballistic launch is first investigated. These will suffice for the immediate purpose, which is to illustrate the range of benefits available from the technique.

It will be taken then that the nett available thrust of the Pegasus 104 in the Sea Harrier will be 19200lb. From this it can be inferred that the Vertical Takeoff weight of the aircraft will be 19200÷1.15 = 17000lb. The maximum takeoff weight of the RAF Harrier GRIII as given in Janes "All the Worlds Aircraft" is 24500lb.

This means that anything that improves on the VTO weight has the potential to increase it by up to 7500lb. This represents an approximate doubling of the aircrafts' payload. To put this possible gain into perspective the following figures may be considered:

* A sidewinder missile weighs about 200lb
* A sparrow missile weighs about 450lb
* 500lb more fuel can increase the aircrafts radius of action by more than 10%

So even a gain of 1000lb, a mere 6%, in the takeoff weight of the Sea Harrier is well worth working for.

The Taylor Thesis

Getting a fixed-wing aircraft airborne from a ship had, until the uncertain dawn of the VTOL era, always been a matter of accelerating the aircraft to a speed safely in excess of its lowest straight and level stalling speed (assisted by slots, slats, flaps and blow) while keeping it firmly in contact with the deck.

While airborne acceleration to this speed from a sub-stalled condition had been tacitly accepted in the definition of V_{15} the minimum launch speed such that the aircraft is not fully wingborne until it has dropped 15ft from flight deck level, use of a longer period of substalled flight with the aircraft in a partially ballistic condition had not been countenanced as an acceptable stage of acceleration, mainly because the aircraft would have been expected to be out of control about all three axes until flying speed had been attained. It was safer to assume that an aircraft would be pulling 1g regardless of its trajectory and that its control surfaces would not be effective before the speed for straight-and-level flight had been reached.

All that changed with the arrival on the scene of the VTOL aircraft with its ability to control itself in sub-stalled speeds, right down to the hover, and indeed even while going astern, by means of some combination of reaction controls and vectored thrust. The first aircraft engineer to realise that this ability to remain under control although below the stall implied that a lower launch speed might work was Lieutenant-Commander Douglas Taylor, Royal Navy.

In 1973 he published a Thesis called "The operation of VTOL Aircraft from Confined Spaces" In it he described how a VTOL aircraft projected into the air with an upward component of velocity in addition to the usual horizontal component could use the time it took to fall back to its launch height to accelerate. If the launch conditions had been correctly chosen, it could expect to reach a horizontal speed high enough to support itself on wings and jets together by the time it returned to its launch height, or even before, and thus a successful launch would have been achieved at a speed lower than that required if the launch projection had been purely horizontal.

The ballistic path taken by the aircraft during its post-launch acceleration phase has become known as the 'Runway in the Sky', and Taylor showed by way of example that at a launch angle of 30° to the horizontal an aircraft weighing 22000lb could be safely launched at an exit speed of only 39 knots compared with the 120 knots which would have been required had the launch path been merely horizontal.

The methods he suggested of achieving this 39 knots were as follows:

* Catapults
* Rocket assisted takeoff
* Free takeoff up an inclined ramp - skijump.

Of these, the Skijump was by far the most attractive. It has no moving parts, it calls for no alteration to the aircraft, such as attachments for Accelerated Takeoff or rocket mountings and controls, and it is for the invention of the Skijump, rather than for the principle of the ballistic launch that he has become best known in aviation circles.

The advantages of a skijump launch over a conventional takeoff are well known in the world of Maritime VTOL, but no apology is made for summarising them once more, as they appear in Ref.2.

Performance:	A 20° ramp equates to a 30 knot wind over the deck, offering:- (a) Much reduced deckroom at a fixed payload. (b) Extra payload for a given deck (c) Elimination of ship pitch dangers at launch.
Handling and Safety:	(a) High trajectory (b) Better pilot survival envelope
Ship:	(a) No need for high speed at launch (b) Thus reduced fuel consumption

In essence, a skijump has the effect of making a long flight deck even longer and transforms a short flight deck into a long one. It is reasonable to infer that even the shortest flight deck could be enhanced by the addition of a skijump of some sort.

The simple curved skijump suffers from three disadvantages, all to do with the curve around which the aircraft travels. To the innovative designer all three of these problems can be regarded as challenges. They are:

a. Curvature

The Harrier is a long aircraft with its nose and main wheels fairly close together, and with a ventral fin and bumper projecting well below the fuselage centreline at the back. The result of this configuration is that the tightest arc of a circle that can be described in the vertical plane to contact all three points must be drawn to a radius of 160ft. This means that whatever advantages a skijump with an exit angle greater than 20° would have, they would be offset by the inescapable problem that the height of the installation would be grotesque - 21 ft for a 30° exit and 37 ft for a 40° exit.

b. Undercarriage

The centrifugal force caused by vertical rotation of the aircraft as it goes round the skijump imposes a normal load on the undercarriage such that in the extreme case it may bottom. The problem is not only a function of the limiting static load the undercarriage can take, it is also a function of the rate at which it can take it. The centrifugal load will increase steadily over a time span of as much as 1 second as the aircraft traverses the skijump, and this compares unfavourably with the 0.05 sec to absorb a landing impact which usually provides the design case for landing gear struts and shock absorbers. So this consideration too calls for a minimum radius of curvature of the skijump track, and so implies a tall and ungainly installation if a skijump is to be built with a high exit angle.

c. Pitching rate

As the aircraft runs around the curve, so it has an upwards pitching motion imparted to it. Then, once the nose wheel clears the lip of the ramp, this upward pitch undergoes an instant reversal as the centrifugal forces acting on the aircraft through its centre of gravity and ahead of the main undercarriage cause it to pitch downwards. The resulting downwards pitch could well exceed the correction force that a full nose-up command could exert. Because of this, the curved portion of the skijump is followed by a plain section approximately the same in length as the aircraft wheel base, so there should be no residual pitching motion left to correct as the aircraft leaves the ramp.

Hence a skijump installation is some 11½ft longer than is theoretically necessary.

The latter problem is the least of the three. The only way to overcome the other two will be by engineering elaboration of the Harrier and the deck, otherwise the limiting exit angle for a skijump launch will have to be held at 20°. A requirement to be able to ride a tighter curve will have to be fed into the specification for the next generation of VSTOL aircraft to go to sea.

Taylor evaluated the output of the simple skijump by use of basic equations of motion for an aircraft in accelerating ballistic flight. His treatment of the subject is described in Appendix 1.

The Skijump in Reality

Between the theory and mathematics in Taylors' original Thesis and the reality of the skijump in its practical application there yawns quite a gulf. The original skijump thesis passed through the hands of both RAE Bedford and Hawker Siddley Aviation before the latter were contracted to design, develop and build a practical demonstrator and it underwent a large amount of alteration at each stage before the first cautious launch from a 6° ramp ever took place.

Major differences in technique

1. Flyaway point

Taylors original idea was to make use of the whole time of flight between the aircraft leaving the point of launch and returning to its original height as a period of acceleration to flying speed. Investigation showed, however, that between a launch from which the aircraft would just manage to fly away when it was back at its launch height, and one in which it would not recover at all once past the peak of its ballistic trajectory, there lies a very fine margin indeed. Accordingly, the technique adopted was to aim to fly off from the apex of the trajectory. But between the apex flyaway and one which just gets to the top and then starts to descend there lurks a further cliffedge of uncertainty. Application of the appropriate factors of safety to even this launch means that it is only the 3-sigma launch that ever gets even as far as the horizontal. So as far as a casual observer is concerned, any normal launch from a skijump has the appearance of just simply projecting the aircraft into a flightpath that is a smooth continuation of the upward slope.

2. Nozzle scheduling

Selection of the best nozzle angle for a skijump launch presents a neat little problem. For the acceleration period up to and around the jump from a standing start, the nozzles should be vectored fairly well aft to make the axial acceleration as high as possible. (In practice a fully aft orientation cannot be achieved as the natural stance of the aircraft is with the fore and aft axis inclined some 8° to the horizontal). Once the aircraft is airborne and initially pointing skywards, what then? If the nozzles are kept pointing downwards then a long period of ballistic-flight will ensue but the acceleration in the horizontal direction will be poor; if they point aft more than downwards, then the horizontal acceleration will be better but the time in which it may take effect will be worse. In the extreme case of a steep exit, say 60°, then the initial nozzle angle to the fuselage is limited to a value of 30° in the ideal theoretical aeroplane, (and considerably less than this in the practical Sea Harrier), and once the aircraft nose has dropped through 30°, all acceleration is in a downwards direction. Clearly the nozzles should be rotated relative to the aircraft during the semi-ballistic stages of the flight in accordance with some pre-determined schedule if the best possible trajectory is to be followed.

Taylor's early calculations illustrated this, and he recognised the complications that would be involved to schedule the nozzle angles in reality. He suggested the nozzle angle should be raised continuously either by means of a servo system connected to a horizontal reference, or by the pilot, who, he conceded is already fairly fully occupied at this stage of the flight, and might find the additional workload to be unacceptable. Nevertheless he considered the advantages of varying the nozzle angle to justify the complexity and expense involved, and the calculations following this assertation were based on the assumption that some method of varying the nozzle angle would be devised and put into practice.

However, the technique currently used for flying off a skijump is for the pilot to select nozzles down to a preset position as he passes a particular visual cue on the skijump surface, and that nozzle position remains inviolate until his aircraft reaches transition speed.

Both the foregoing notes could be interpreted as criticisms of the original skijump thesis in their implications that the benefits to be gained are nothing like as great as those which were promised. Nothing could be further from this writers intention. They each serve to illustrate the extent to which the adaptation of a fine idea to practical operation must inevitably moderate the brightness if its attaction, in some cases even douse it altogehter. Skijump is not immune from this, and although its detail theory has been extensively modified in order to satisfy the requirements of practicality, the brilliance of the idea at its core must remain undiminished.

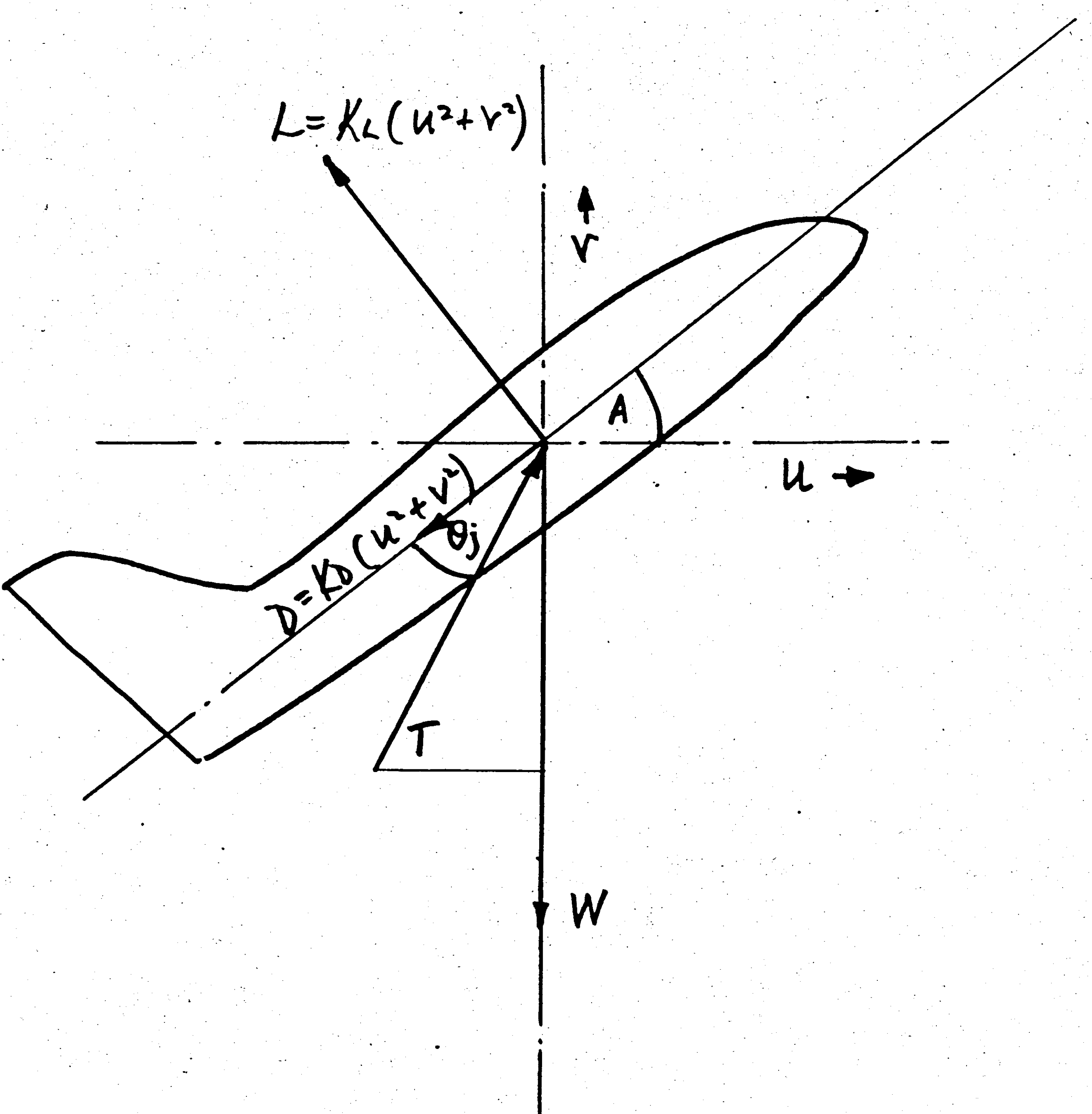
Retracing the steps

As stated in the Introduction, the object of this paper is to review the principle of the ballistic launch and examine its suitability for use in sub-capital ships.

The first step is to rework the ballistic theories from Taylors thesis and see what can be learned. So the original equations of motion (Appendix 1) were gratefully seized upon and set to work once more. Taylor had developed his theory to cover a full ballistic trajectory back to launch height for the flyaway point and he had assumed some system of nozzle angle scheduling in flight in order to fly the most rewarding trajectory. What needed to be done first was to see whether the conclusions he drew from his researches remained valid with a fly-away point now no longer at the end of the parabola but instead at the top of the climb.

It is tempting to set up a pair of equations of motion as for an aeroplane and then believe that the abstraction to which they are applied will by some gift perform like an aeroplane. For instance if the forces balance one can assume the aircraft is hovering, and from that is is but a short (but shaky) step to assume it to be hovering both stably and in a sensible attitude. This observation follows the discovery that a flyaway could apparently be achieved at speeds well below the notional stalling speed from which we derived the original equations of motion. Examination showed that such cases were quite possible with the aircraft at an attitude such that it was practically standing on its jets and with adequate wing lift derived from its forward speed to maintain the balance. A simple calculation for flyaway speed for a range of weights and angles shows this to be valid (Appendix 2). Consolation comes from the realisation that for the Lift and Drag constants of the equations of motion to be valid, the airstreams direction must remain constant also, and this makes a welcome tie-up with reality in as much as the pilot controls his aircraft off the skijump by maintaining a constant reading on the Airstream Direction Detector. So the flyaway speeds are attained with the aircraft at a reasonable angle and moving in the right direction. It is not quite so easy to claim that the aircraft is stable and fully controllable in these conditions.

Al-1-Fig.1.



FORCES AND VECTORS ON A BODY IN UPWARD FLIGHT

EXPERIMENTAL PROGRAM

Ballistic Launch with Jet Deflection fixed relative to Aircraft - SKIJ

The Taylor thesis takes the aircraft right on the peak of its trajectory and back to its launch altitude, and makes all the time taken available for acceleration. Consideration of the physical implication of this shows that the exact launch speed for which this transition is just achieved will be very finely timed indeed. One foot per second slower and the aircraft must sink below its launch height. One foot per second faster and the aircraft will describe a very shallow curve that never dips quite as far as the launch altitude. Clearly the practical launch speed must be such that the risk of achieving a less-than-average launch must be less than 1/1000. Therefore the new 'average' launch will have a high flyaway point. The question is, does an increased launch speed erode too deeply into the advantages offered by the original scheme?

To investigate what happens to a VTOL aircraft launched under these conditions, a simple program was devised in FORTRAN 4 to produce the maximum horizontal speeds achieved at the crest of the trajectories flown by aircraft of varying weight, launch speed, launch slope and jet deflections. The technique that Taylor used was used again, together with his equations of motion, the differences being that time intervals of 0.01 sec were used in preference to Taylor's original 0.1 sec, which had been found to produce too coarse a result. Printout followed the state where either:

a. The vertical velocity had dropped to approximately zero, indicating that the peak of the trajectory had now been reached and the aircraft was now starting to descend, or

b. The downwards increment in vertical velocity had dropped to approximately zero, indicating that the aircraft was going to fly away before the peak was attained.

The program, SKIJ, is shown in Appendix 3, together with a representative selection of the results obtained.

Most of the figures shown are the results of launch speeds which were too low to lead to a flyaway. Choice of these speeds was deliberate, the object being to illustrate what could be gained from a ballistic launch, (regardless of how it may have been executed) and to show the effects of varying the parameters most readily open to changes.

Observations

The general observations that can be made from the results of Program SKIJ are as follows:-

1. Launch Angle

Peak speeds are at their highest where the launch angle is 40°-50°. There is nothing to be gained from using a higher exit angle, indeed above about 50° the benefits of the technique rapidly tail off and can be seen to reverse.

So allowing for the possibility of ship motion in pitch, (or in roll, if a beam launch is to be considered), being enough to add a noticeable amount to the launch angle set, it can be seen that the steepest useable launch angle is 40° or so. Even this implies an ungainly installation, and as the difference gain in performance between 30° and 40° is relatively small, compared with that between 20° and 30° for instance, an upper limit of 30° would seem reasonable. Later investigations are shown to produce results that satisfactorily endorse this view.

2. Jet Deflection

The best jet deflections are such that the sum of Jet Deflection and Launch Angle is about 70°. At the steeper launches it is obviously advantageous to carry as much weight as possible on the jets. This means, though, that there will be less thrust component available to give the aircraft a reasonable value of horizontal accelerations, so the better performance will be achieved at a cost of the period of ballistic flight being longer. This might not be acceptable in practice as the engine is at full power all this time, and also there is a greater demand on the pilot who has to hold in set value of ADD for a longer period with consistent accuracy. Fig.3.5 illustrates that the best apparent performance can take twice as long to achieve as will that leading to a peak speed only 10ft/sec less.

3. End Speed

Fig.3.3 shows that a given increment in launch speed is repaid about twice over at the peak condition. The value of this reward is increased even further as the speed for successful flyaway is approached.

At first sight this appears to be an attractive characteristic, that the last ft/sec squeezed out of the aircraft at launch is worth two or more in final achievement. However it does mean that getting an exact flyaway speed will be very closely dependent on the accuracy of the speed at the point of launch. The practical implications of this is that there will have to be a large factor of safety imposed on the launch speed, and the more speed-sensitive potential benefits will have to be foregone.

Ballistic Launch with Jet Deflection fixed relative to horizons - SKIK

A simple amendment to the program SKIJ enables the condition of holding the jet deflection constant to the horizon to be explored. The amended program, SKIK, was run for the same series of variables as was SKIJ, and is shown, together with the results obtained, at Appendix 4.

Comparison with the results of SKIJ (i.e. comparing Figs. 4.1, 4.2 with 3.1 and 3.2), shows a much better available performance over the middle range of conditions, but there is a menacing sensitivity to launch angle around the peak conditions. Too high a launch angle can be just as bad as one too low, and the effect of just a few degrees past the peak is very marked. The implications of this in connection with a forward launch in a ship which is pitching heavily, or a beam launch in a ship which is rolling heavily, must be considered when debating just how far to push the benefits available from a ballistic launch.

Observations

The following observations can be made from examination of the SKIK results:-

1. Launch Angle

While 50° appears to be the angle giving the highest performance, the peakiness of the result must effectively rule out the adoption of this figure for practical purposes. As with SKIJ, Appendix 3, a maximum launch angle of 40° or so seems a more prudent one to use while 30° looks safer still, with only a small drop in performance to accept.

2. Jet Deflections

Again the best results occur where the combined totals of Launch Angle and Jet Deflection are about 70°, and they occur too when launch angles are in the higher ranges. As with SKIJ, the reason is not hard to deduce, and comparisons of 4.5 with Fig.3.5 shows that the higher performance is achieved at a cost of a longer period of flight, with all the consequential penalties which that entails.

At very high launch angles the aircraft is almost standing on its jets, and with the jet angle now constant in space, the acceleration in the horizontal direction is never going to increase.

Ballistic Launch with Jet Deflection varied in flight:SKIL

To devise some system capable of holding the jet deflection constant in space, as described in the Taylor thesis and considered in the previous section would inevitably be complicated and expensive. It might also be unnecessary to go into such elaborate detail, after all, the jet deflection is scheduled in effect while the aircraft and jets rotate after a jet-fixed launch.

If a schedule were to be devised it would most likely be required to be one to set the jets somewhere between the fixed-to-the-aircraft locus and the fixed-in-space locus. As the aircraft rotates downwards after launch, the jets should swing forwards in order to keep a vertical component effective for longer. If the pilot were to defer his 'down' selection until some point after exit from the launcher, this would be some improvement on having the nozzles 'fixed' in flight relative to the aircraft, and it would also mean that the period during which they were accelerating the aircraft along the ramp would be longer.

The original program SKIJ was altered yet again, this time to include a loop during which the jets are progressively lowered from 10^{o} to 50^{o} over a period of 1 sec, initiation of this process being at some specific time point between 0 and 3 seconds after launch.

The program SKIL and the results obtained from it are at Appendix 5.

Observations

It can be seen from Fig.5.1 that this simple nozzle scheduling operations can not only do as well as the hypothetical fully automatic one, but for certain ranges of values it can even do better.

Figures for the best peak speed achieved are tabulated below:

Aircraft weight = 22500 lb; Launch angle = 40^{o}

Launch Speed ft/sec	Nozzle Technique		
	SKIJ	SKIK	SKIL
60	95.3	113.4	114.5
70	111.7	135.2	138.4
80	128.3	160.6	166.9

As in all skijump exercises, even the simplest technique offers surprisingly large returns. (In Ref (2) the figure of 66 lb payload per knot, i.e. 40 lb/ft/sec is quoted). Lowering the nozzles after launch, (a technique disallowed in both Refs 1 and 2) seems to offer the best return of all, especially off a launch at a high angle.

Fig.5.2 shows that for launch angles higher than 40° better results are obtained if the onset of jet deflection is delayed progressively more and more as the angle increases. The inference is that the best results will occur at the highest angles if jet deflection is postponed indefinitely, (which brings us back to keeping the jet deflection constant as in SKIK, Appendix 4, and thereby achieving an impressive gain in speed although at the cost of a long period of sub-stalled flight).

The difference in gain between the 40° launch and the 55° launch is only about 15ft/sec. The times taken are 7.7 secs and 10.3 secs respectively, while the time taken for the nozzle-fixed SKIJ flight is 3.1 secs. Therefore (7.7 - 3.1) sec = 4.7 secs is worth an extra 31ft/sec while (10.3 - 7.7) secs = 2.6 secs is worth a further 15ft/sec. It seems safest and easiest to accept the benefits of an instantly-demanded nozzle selection at exit from a 40° launch, and maybe gain a small amount if the pilots' reactions are delayed., than to seek the higher rewards obtainable from a cold-blooded 1.5 sec delay off a 55° launch.

Calculations of Launch Speeds

So far the ballistic launch has been explored by means of setting up a range of launch conditions and seeing what peak forward speeds can be achieved from them. The next step in development of the idea is to define a flight condition, set up a range of aircraft weights, launch angles and jet deflections and find out what the appropriate speeds for launch must be.

Once again the nature of the mathematical approach employed makes up in simplicity what it lacks in subtlety. The condition for flight achievement was set up as being a state in which the vertical speed is not less than +5ft/sec. this definition following the spirit that defined a catapult Minimum Launch Speed as being that speed from which the worst consequence would be a dip of 5ft below the level of the Flight Deck. Another consideration giving rise to the arbitrary flight definition was that, as explained before, once an aircraft is allowed to start to descend below the apex of a skijump launch it can be very difficult to coax it back up again.

To evaluate the launch speeds, the framework of the original program SKIJ was used as the basis for further programs, SKIM and SKIP, the one with the jet deflections being left as set at launch and the other, being analogous to SKIK, with the jets scheduled to hold a constant angle of depression throughout the ballistic stage of the flight.

Both programs and a selection of their results are at Appendix 6.

A first glance at Appendix 6 and Fig.6.1 shows that a launch speed of only 60 ft/sec (36 knots) is theoretically capable of giving a safe launch to an aircraft with an All-up-weight of 21000 lb at a launch angle of 30°, given full scheduling of the jets to maintain a constant angle in space.

Theory has to be toned down a lot before safe practice can follow. The sensitivity of this theoretical launch to the slightest change in value of one parameter is illustrated by two consecutive lines from an early output from the fixed-nozzle program SKIM:

Weight	Jet	Angle	Launch	T	U	V
17760	30	35	62.0	0.01	50.9	35.56
17770	30	35	62.0	8.10	242.1	5.15

At 17760 lb the aircraft flies straight away from the launcher and there is no ballistic flight phase at all.

An increase in weight of a mere 10 lb is enough to call for a ballistic trajectory to be necessary before wing-supported flight can establish itself, and so another 8 seconds of flight was necessary.

It can be seen from Figs.6.2a, b and c that while 40° offers the best exit angle outside optimal conditions it does not offer the lowest ultimate launch speed, and also the lowest launch speeds for each launch angle are all very similar. Again a 30° angle is far superior to one of 20° and seems to be the best all-round launch angle wherever mechanical and structural considerations permit. The data supporting the case for 30° is tabulated below:-

Table of Lowest Launch Speeds (ft/sec), Jet Angle 50°

Weight	Launch Angle 20°	30°	40°
20,000	68	52	47
21,000	85	70	70
22,000	102	89	95
23,000	119	107	121
24,000	134	125	227

A program for assessing the results of manually scheduling the nozzles at the point of launch, rather than assuming instantaneous selection immediately before launch, was assembled from SKIM and the iterative loop of SKIL.

Called SKI1 it produced results as follows:-

Manual Scheduling 10°-50°; 30° launch

Weight	Speed	'SKIM' speed
21,000	85	70
22,000	101	89
23,000	116 .	107

While the results of manual scheduling are not as good as those for which an instantaneous depression is assumed, it must be remembered that only one scheduling rate and range has been evaluated. The possibility still remains that further exploration of this launch technique might yield more favourable results. The basic program SKI1 is included in Appendix 6.

Systems Sensitivity

A general survey of the figures in Appendix 6 shows that the sensitivity of the launch speed to variations in each of the conditions considered appears to be as follows:-

* Increase in launch speed for 1000 lb increase in All Up Weight = 20 ft/sec

* Increase in launch speed for 1° change in nozzle angle = 2ft/sec at low weights
= 1ft/sec at high weights

* Increase in launch speed for 1° change in launch angle = 1 ft/sec

So taking Figs.6.2a and 6.2b as a guide, it follows for an aircraft of 21,000 lbs all-up weight which might be in error by 1%, with its nozzles set at 50°, accurate to 2°, and launching from a ship with 2° motion in the direction of launch, the safe launching speeds would be:-

Skijump at 20°:

$$V = 85 + (\frac{210}{1000} \times 20) + 2 \times 2 + 1 = \underline{95 \text{ ft/sec}}$$

Launch at 30°

$$V = 70 + (\frac{210}{1000} \times 20) + 2 \times 2 + 1 = \underline{79 \text{ ft/sec}}$$

Rounding up to the next 5 ft/sec, a family of launch speeds would be as follows:-

Weight	20° Skijump	30° launch
19,000	55	45
20,000	75	65
21,000	95	80
22,000	115	100

The Shallow Skijump

Given the space for manoeuvre, any rolling launch of a Harrier type aircraft can hardly fail to be an improvement on a vertical takeoff with its extra penalties of exhaust gas reingestion and suck down effects.

The first skijump launches were conducted off an angle of 6° only, and even this imparts a remarkably high advantage to the aircraft compared with a straight and level departure, particularly in the case of a low all-up weight.

Tabulated below are the results of running the program SKIM designed for calculating launch speeds for an aircraft weighing 19,000 lb and with net thrust of 19200 lb.

Jet deflection	Launch Angle	Launch Speed(ft/sec)
50°	6°	101
	7°	95
	8°	89
	9°	84
	10°	79
55°	6°	84
	7°	77
	8°	72
	9°	67
	10°	63

The end speeds required for rolling takeoff at the same jet deflection angles are:

50° - 178 ft/sec
55° - 156 ft/sec

While the launch speeds as tabulated look encouragingly low, note should be taken of their extreme sensitivity to both Jet Deflection and Launch Angle; about 3ft per second per degree in the first case and about 6ft per second per degree in the second. Evidently, in practice, a lot of the apparent advantage is likely to be eroded away by imposition of factors of safety. Even so, the remaining gains are worth harvesting.

Correction for Wind over Deck

For skijump launches into wind, (as distinct from across wind if a beam launch were ever considered), the effect of a horizontal wind at least to a first approximation, is to reduce the horizontal component of launch velocity required, having the vertical component unchanged. The persistence of this vertical component explains why allowance for WOD is not done by simple linear subtractions. Nevertheless a strong opposing wind over the deck brings about a dramatic reduction in the launch speeds required for given conditions, and WOD is always assumed to be active in all the brochures in which the benefits of the Skijump Harrier are described.

Using the program SKIM (nozzles set at launch and remaining unaltered relative to the aircraft) a range of minimal exit speeds from a 15° skijump was procured. Correcting for wind-over deck was carried out as shown in the following example:

AUW = 22000 lb; Minimum endspeed = 102 ft/sec

= 61.2 knots

$$\text{Horizontal component} = 61.2 \cos 15^{0} = 59.11$$

$$\text{Vertical component} = 61.2 \text{ Sin } 15^{0} = 15.84$$

With a 20 knot headwind the net horizontal component

$$= 59.11 - 20 = 39.11$$

$$\text{Recalculated launch speed} = \sqrt{39.11^2 + 15.84^2}$$

$$= \underline{42.19}$$

Over a wider range of weight values the corrected endspeeds would be as follows:

Aircraft weight (lb)	Endspeed (knots)
20500	23
21000	29.14
21500	36.25
22000	42.19
22500	48.75
23000	54.50

These are shown plotted in Fig.2. (The dotted line on the same graph shows the figures computed by RAE Bedford for the same conditions, and demonstrates correspondence at an encouraging level).

Effect of Variations in Engine Thrust

For all computations carried out so far the nett engine thrust has been used steady at a value of 19,200lb.

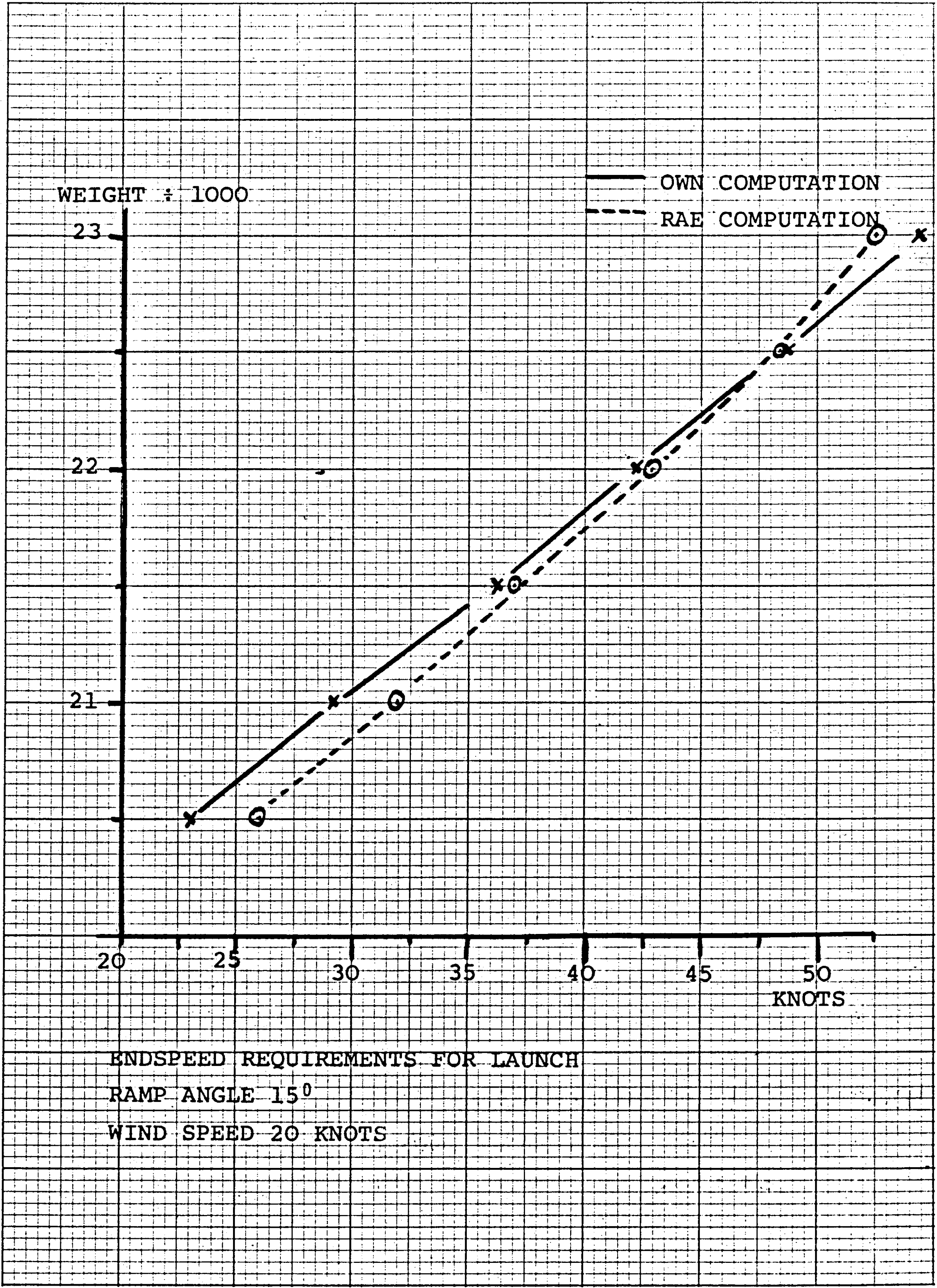

OWN COMPUTATION
RAE COMPUTATION
WEIGHT ÷ 1000
23
22
21
20
25
30
35
40
45
50
KNOTS
ENDSPEED REQUIREMENTS FOR LAUNCH
RAMP ANGLE 15°
WIND SPEED 20 KNOTS

FIGURE 2

At full power, a variation of ±1% in fan speed will result in a corresponding variation of thrust of ±500 lb or so. What might this imply in practice?

The model was run again with thrust values of 19200±800 lb and the results in endspeeds required off a 15^0 skijump in still air are shown below:

Endspeeds in zero wind

(All figures in ft/sec)

Aircraft Weight	Thrust (lb) 18400	 19200	 20000
20,000	74	51	-
20,500	87	66	-
21,000	98	79	-
21,500	109	91	71
22,000	119	102	84
22,500	129	113	96
23,000	139	123	106
23,500	148	132	116
24,000	156	142	125

It is readily apparent that a 1% rpm variation is accompanied by a change in exit speed of about 18 ft/sec. At a constant acceleration of 25 ft/sec^2 this could mean an extra deck run, taking an aircraft weight of 22500 lb for an example, given by

$$(129^2 - 113^2) = 2 \times 25 \times \text{Distance}$$

from which the extra run is found to be no less than 77ft.

In practice this difference will be even greater as differences in thrust will result in differences in acceleration along the deck, with the aircraft with the less powerful engine needing an even longer run to reach the end speed required. Here is the source of another safety factor which will nibble at the edge of the advantages a skijump launch can offer. This will be discussed at more length in the next part of this study in which the subject of takeoff distances will be considered.

CONCLUSIONS

1.a. The skijump launch offers performance gains which increase with increasing exit angles up to 40^0, after which the benefit becomes increasingly peaky and then starts to diminish. The advantages that 40^0 confers over 30^0 are of the order of only a few feet per second in launch speed, and so all else being equal, the better angle for a ballistic launch would be about 30^0.

b. If the aircraft is self-propelled at the launch then considerations of ship and aircraft structure and shape reduce this angle to about 20^0, although with little further loss. Even an exit angle as low as 6^0 gives a marked improvement over a flat deck.

2. Investigation of the effects of scheduling nozzle angles in flight show that further performance advantages can be gained in theory. Study of Fig.6.1 shows that keeping the nozzles at an angle fixed relative to the horizon could lead to a reduction of 10-15 ft/sec in the value of the minimum launch speed, compared with setting them relative to the aircraft, and similar results are obtained for other combinations of aircraft weight and launch angles.

It is possible that further refining of the scheduling of the nozzle angles could bring about even greater improvements, but with so many variables to play about with, a full exploration of the problem would call for considerable effort in computer analysis, while the potential return would be only a matter of a reduction in end speed of a dozen feet per second or so. The benefits of the straightforward skijump can be measured in scores of feet per second, and therefore such an exercise is not considered to be worthwhile at this stage of the study.

3. The methods of computation used in this paper have been shown to produce results which over the range of weights and angles being considered bear comparison with those produced more formally in practice, vide Fig.2. Accordingly they are considered to be valid enough to carry forward to the next section of this study which will be concerned with methods of initiating a ballistic launch.

APPENDIX 1

ORIGINAL TAYLOR THESIS EQUATIONS OF MOTION

The forces and vectors considered for a body in upward flight under the influence of aerodynamic forces and vectored thrust are shown in Fig.1.

Horizontal Acceleration is given by:

$$\dot{U} = \frac{g}{W}\left[T\cos(A + \theta_j) - \sqrt{U^2 + V^2}\,(K_L V + K_D U)\right]$$

Vertical Acceleration is similarly given by:

$$\dot{V} = \frac{g}{W}\left[T\sin(A + \theta_j) - W + \sqrt{U^2 + V^2}\,(K_L U - K_D V)\right]$$

where K_L and K_D are $\frac{1}{2}\rho SC_L$ and $\frac{1}{2}\rho SC_D$, being constants of Lift and Drag respectively.

Working values appropriate to the Harrier aircraft for these constants were obtained from the following reasoning:

For this aircraft - net thrust = 19200 lb

Lift/Drag ratio in takeoff conditions with deflected thrust= 5:1

An aircraft can sustain vertically unaccelerated level flight at a Weight of 22000 lb, jet deflection to the horizontal of 60° and forward speed of 120 knots (200 ft/sec)

So Lift = Weight, therefore

$$\frac{22000 - 19200\sin 60^\circ}{200^2} = K_L$$

Hence $K_L = 0.1343$

and $K_D = K_L/5 = 0.0269$

Even given these values, which were used for all subsequent calculations, it was still difficult to integrate the equations of motion. Taylor used a time-step method. He first resolved his upwards launch velocity into its horizontal and vertical components U and V. Then assuming acceleration to be uniform, at least over a short time interval, he worked out the increments of U and V and used these to produce a new pair of values from which he repeated the process, eventually evaluating the whole trajectory in this manner.

At every step the angle between the aircrafts' flight path and the horizontal is $\text{Tan}^{-1}(V/U)$, and the constants of Lift and Drag remain valid so long as the aircraft maintains its attitude against this angle. In practice this is achieved by having the pilot fly his aircraft in pitch so as to hold a constant ADD (Airstream Direction Detector) angle. (The angle currently flown off Skijump is +12°. This angle is favoured, not so much because of optimal properties it may confer to the flight path, as because the Head Up Display is calibrated 0°, 4°, 8°, 12°, 16° and 20°, of which 8° is not enough and 16° is, apparently, strictly for the aces).

Taylor's calculations were carried out first of all laboriously using a hand calculator and subsequently by using a WANG 3000 digital computer, using a simple program in BASIC. Throughout his study he strove to keep it simple. Further work however is referred to as having been done on a computer at Hawker Siddley Aircraft Limited, by which stage it may safely be assumed that expert refinements were being inforporated into the initial simple system.

APPENDIX 2

FLYAWAY SPEEDS

As discussed in Appendix 1, our hypothetical aircraft will remain in vertically unaccelerated flight given

Weight = 22000 lb
Jet deflection = 60° relative to aircraft
Thrust = 19200 lb
Speed = 120 knots = 200 ft/sec

whence: $(\frac{1}{2}\rho SC_L) \times 200^2 = (22000 - 19200 \sin 60^{\circ})$

and so $\frac{1}{2}\rho SC_L = 0.1343$

So a range of speeds for self supporting flight may be calculated using

$$V^2 = (W - 19200 \sin \theta_j^{\circ})/(0.1343)$$

These are tabulated for values considered in Table 1.

W ÷ 10	10°	20°	30°	40°	50°	60°	70°
20	352	316	278	238	198	158	121
22	373	339	304	268	233	200	172
24	392	360	327	295	263	234	210
26	411	380	349	319	290	264	243

TABLE 1

These values are of interest when studying the maximum speeds achieved by the launch methods evaluated in Appendices 3, 4 and 5. However, flyaway conditions can be seen to occur at speeds lower than those appropriate to the weight. The reason for this is the aircraft in a climb of say 15° and a jet deflection of 60° has an effective jet deflection of 75° and the thrust will therefore support an extra amount of weight equal to $19200(\sin 75^{\circ} - \sin 60^{\circ})$lb

= 1918 lb in this instance.

A simple program for calculating the flyaway speed for all conditions by solving the equation

$$\text{Speed} = \text{SQRT}\left[\frac{(\text{WEIGHT} - 19200\ \text{SIN}(\text{ANGLE} + \text{JET}))}{0.1343\text{COS}(\text{ANGLE}) - 0.0269\text{SIN}(\text{ANGLE})}\right]$$

as at Annex A.

```
        LIST JUMP
     MASTER PROG
     INTEGER WEIGHT,ANGLE
     WRITE(2,60)
     WRITE(2,70)
     WRITE(2,80)
     WEIGHT=17000
     JET=10
     ANGLE=0
     IF((JET+ANGLE).GE.70)GO TO 50
     A=ANGLE*3.1416/180.0
     B=JET*3.1416/180.0
     C=WEIGHT-19200*SIN(A+B)
     D=0.1343*COS(A)-0.0269*SIN(A)
     IF((C/D).LE.0.0)GO TO 50
     SPEED=SQRT(C/D)
     WRITE(2,90)WEIGHT,JET,ANGLE,SPEED
      NGLE=ANGLE+5
     IF(ANGLE.LE.60)GO TO 5
0    JET=JET+5
     IF(JET.LE.60)GO TO 4
     WEIGHT=WEIGHT+500
     IF(WEIGHT.LE.24500)GO TO 3
0    FORMAT(10X,'ENDSPEEDS FOR FLYAWAY',/)
0    FORMAT(10X,'WEIGHT  JET     ANGLE  SPEED')
0     FORMAT(10X,'    LBS     DEG       DEG     F.S',/)
0    FORMAT(11X,3I6,F10.1)
     STOP OK
     END
     FINISH
1.18.01←
```

APPENDIX 3

LAUNCH WITH JET DEFLECTION FIXED RELATIVE TO THE AIRCRAFT-SKIJ

Using the program SKIJ (shown at Annex A) a series of runs was made with aircraft weights ranging from 20500 to 22500 lb, end speeds of 60, 70 and 80 ft/sec and a whole range of launch angles and Jet Deflection angles.

The significant output parameter of interest is the speed at the top of the trajectory. The difference between that speed and the speed of launch illustrates the benefit that an inclined ballistic launch can offer.

ANNEX A TO APPENDIX 3

```
      MASTER PROG
C     SKIJUMP JETPIPE  FIXED RELATIVE TO AIRCRAFT
C     MAIN CALCULATION
      INTEGER WEIGHT,ANGLE
      WRITE(2,98)
      WRITE(2,100)
      WRITE(2,103)
1     WEIGHT=22500
2     JET=10
3     ANGLE=40
4     LAUNCH=70
      IF((JET+ANGLE).GT.80)GO TO 99
5     A=ANGLE*3.1416/180.0
6     B=JET*3.1416/180.0
7     U=LAUNCH*COS(A)
8     V=LAUNCH*SIN(A)
      T=0.1
9     W=ATAN(V/U)
      C=SQRT(U**2+V**2)
      X=.322*(19200*COS(W+B)-(0.1343*V+0.0269*U)*C)/WEIGHT
      Y=.322*(19200*SIN(W+B)-WEIGHT+(0.1343*U-0.0269*V)*C)/WEIGHT
      U=U+X
      V=V+Y
      IF(V.LE.0.0)GO TO 20
      IF(Y.GT.0.0)GO TO 20
      T=T+0.01
      GO TO 9
 20   WRITE(2,200)WEIGHT,JET,ANGLE,LAUNCH,T,U,V
      LAUNCH=LAUNCH+10
      IF(LAUNCH.LE.85)GO TO 5
      ANGLE=ANGLE+5
      IF(ANGLE.LE.55)GO TO 4
99     JET=JET+10
      IF(JET.LE.15)GO TO 3
      WEIGHT=WEIGHT+1000
      IF(WEIGHT.LE.21500)GO TO 2
98    FORMAT(10X,'JETPIPE FIXED RELATIVE TO AIRCRAFT',/)
100   FORMAT(10X,'WEIGHT  JET   ANGLE  LAUNCH       T      U     V')
103   FORMAT(10X,'  LBS.  DEG.   DEG.     F.S.      SEC   FT/S  FT/S')
200   FORMAT(11X,I5,3X,I2,3X,I3,3X,I5,4X,F5.1,2X,F5.1,2X,F5.2)
      STOP OK
      END

      FINISH
10.56.24←
```

JET DEFLECTION FIXED : SKIJ

EFFECT OF VARYING LAUNCH ANGLES FOR VARIED JET DEFLECTIONS

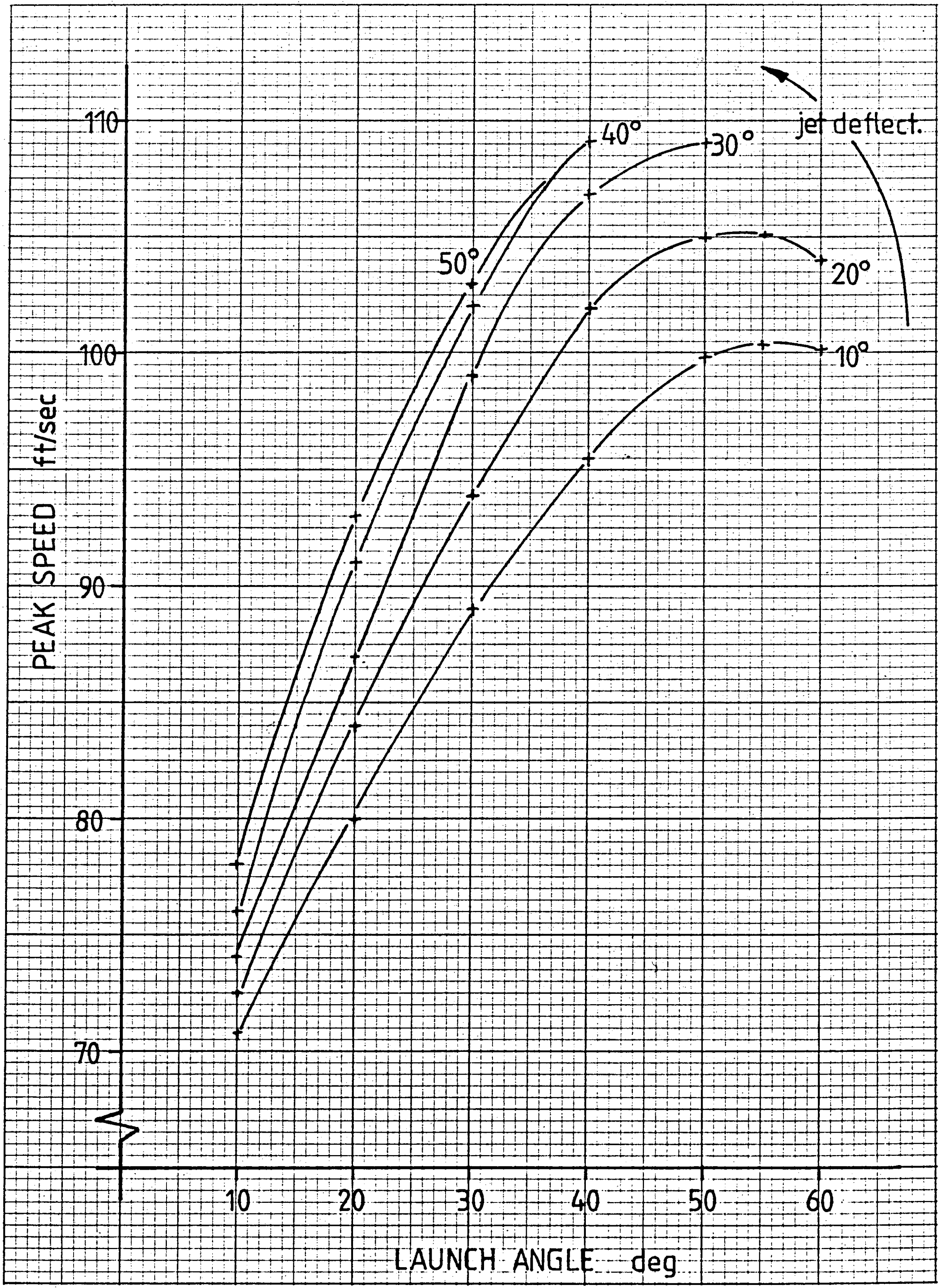


FIGURE 3.1

EFFECT OF VARYING JET DEFLECTION FOR VARIOUS LAUNCH ANGLES

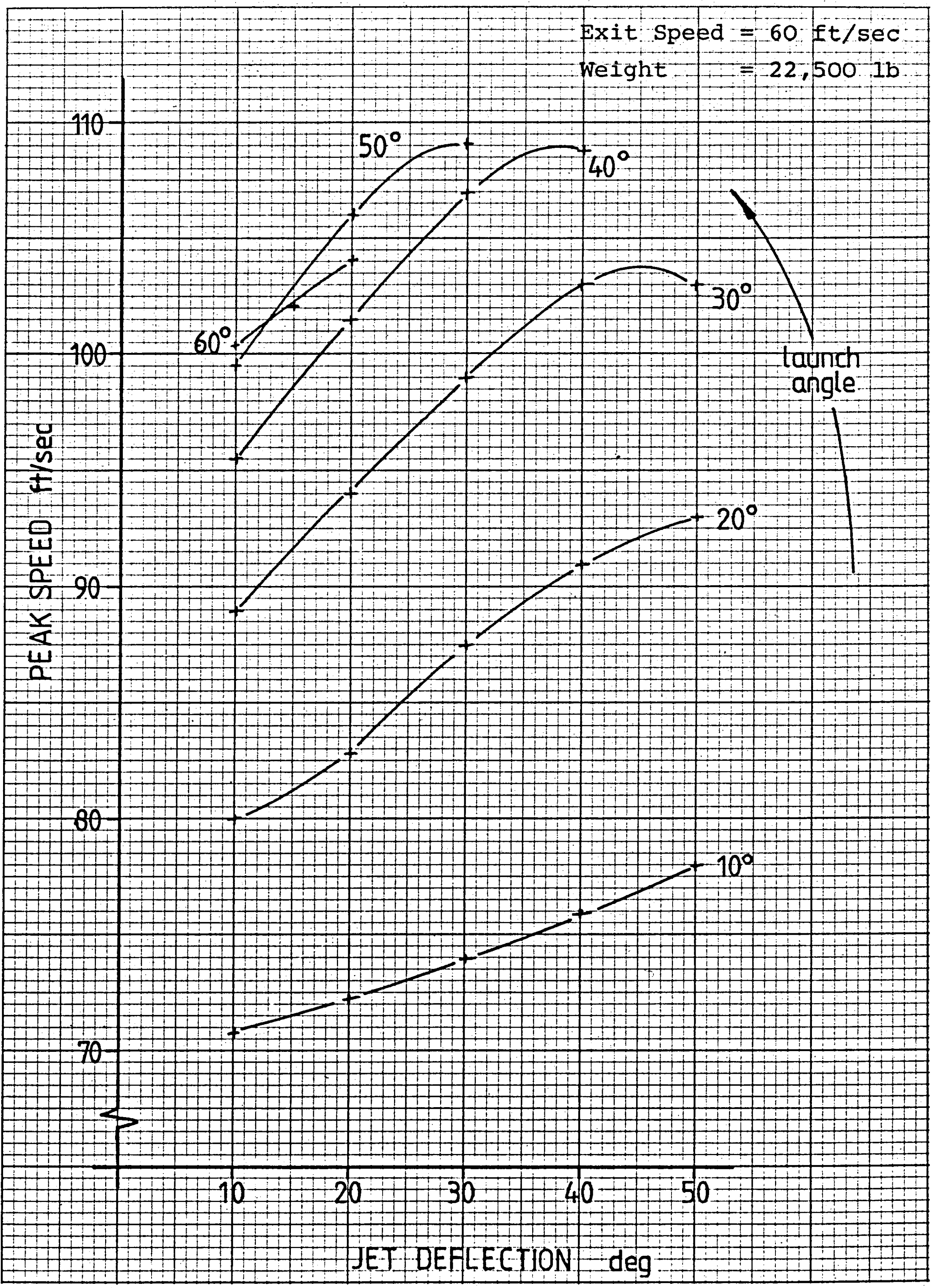


FIGURE 3.2

EFFECT OF VARYING ENDSPEEDS WITH VARIED JET DEFLECTIONS

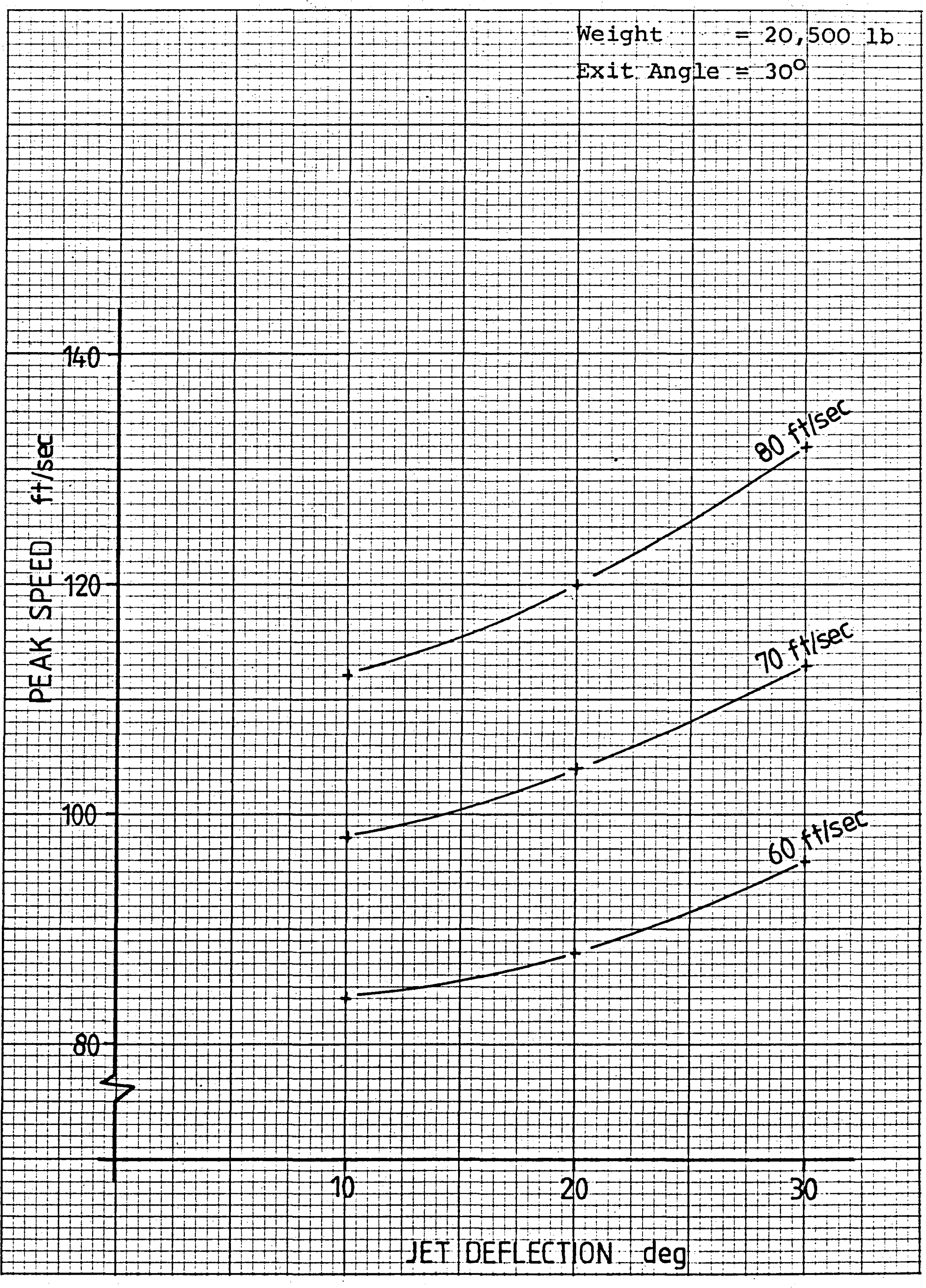


FIGURE 3.3

APPENDIX 3

JET DEFLECTION FIXED : SKIJ

EFFECT OF WEIGHT VARIATION FOR VARIOUS JET DEFLECTION

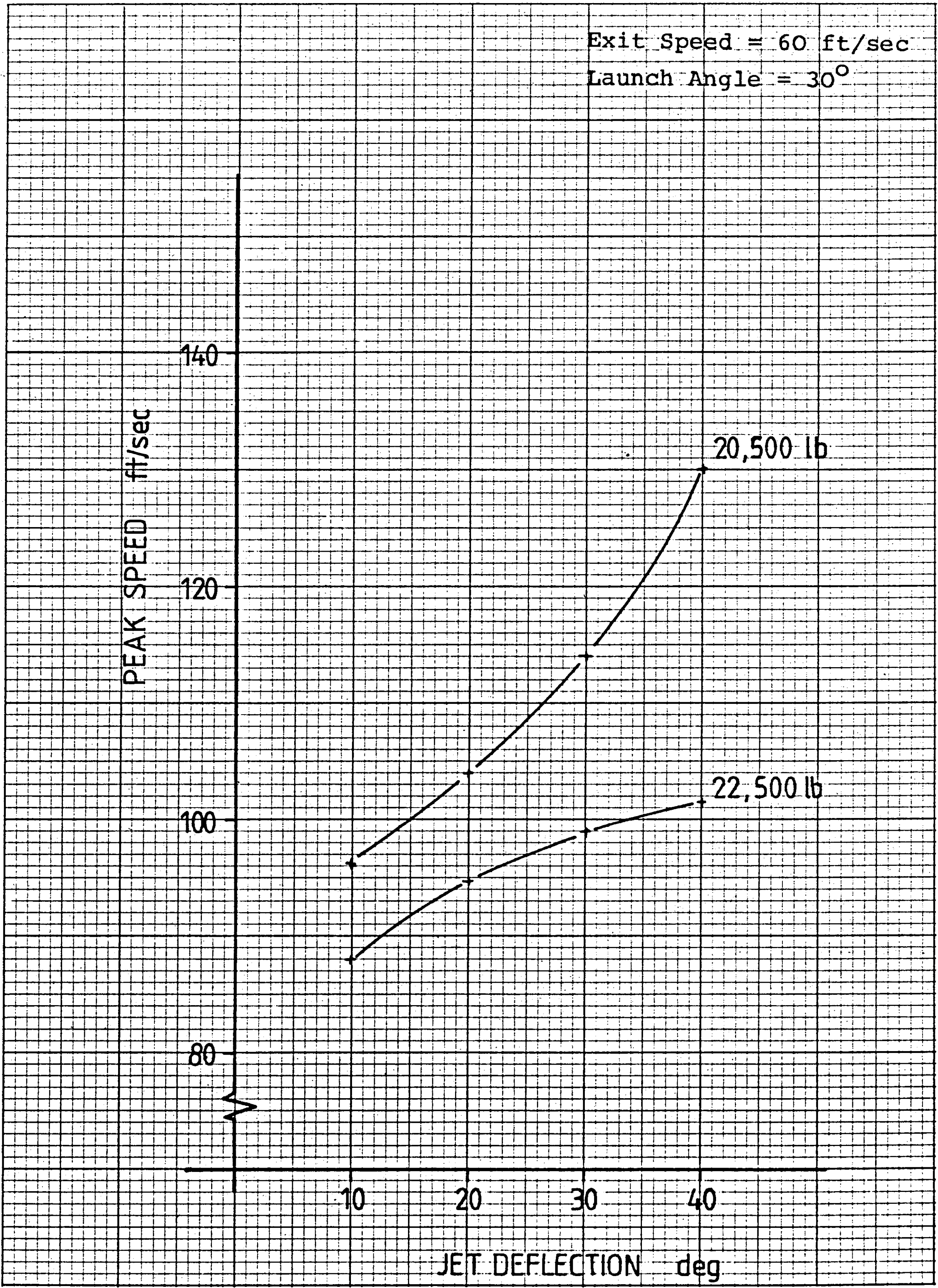


FIGURE 3.4

APPENDIX 3

JET DEFLECTION FIXED : SKIJ

FLIGHT TIME TO ACHIEVE BEST PERFORMANCE

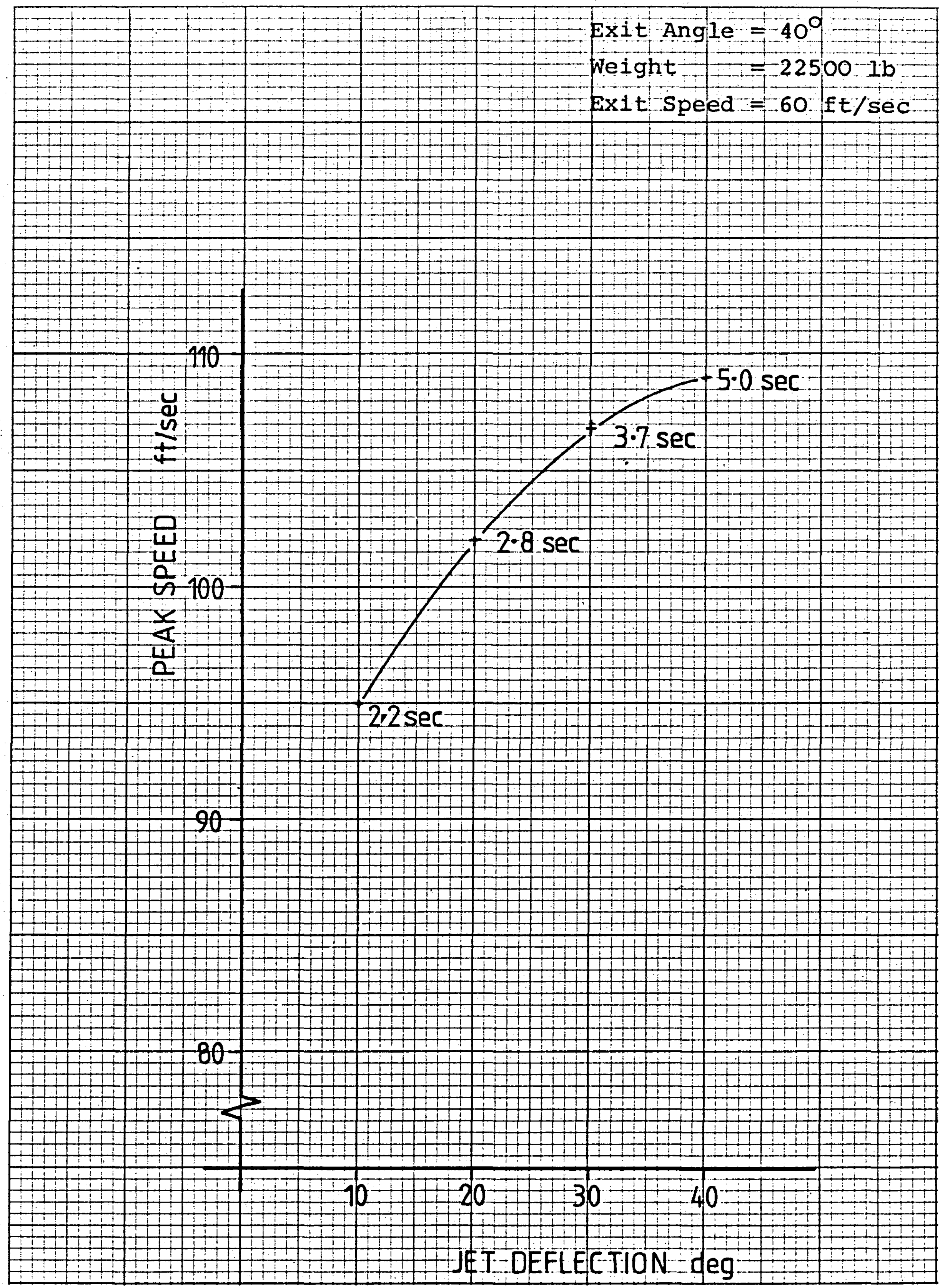


FIGURE 3.5

APPENDIX 4

LAUNCH WITH JET DEFLECTION FIXED RELATIVE TO HORIZON - SKIK

In the program SKIJ (Appendix 3 Annex A), the jet deflection is maintained constant relative to the aircraft, so the jet vector moves back as the aircraft nose drops during the semi-ballistic climb to the top of the trajectory. Forward acceleration increases, but the amount of aircraft weight supported by the jets decreases. A small alteration to the program SKIJ, whereby the jet angle is held constant and not recalculated at each step of the flight, gives rise to the program SKIK (shown at Annex A), which was evaluated for the same range of weights, angles and speeds.

ANNEX A TO APPENDIX 4

```
       MASTER PROG
       SKIJUMP JETPIPE  FIXED RELATIVE TO HORIZON
       MAIN CALCULATION
       INTEGER WEIGHT,ANGLE
       WRITE(2,98)
       WRITE(2,100)
       WRITE(2,103)
       WRITE(2,102)
       WEIGHT=22500
2      JET=10
3      ANGLE=40
4      LAUNCH=70
       IF((JET+ANGLE).GT.80)GO TO 99
5      A=ANGLE*3.1416/180.0
       B=JET*3.1416/180.0
7      U=LAUNCH*COS(A)
8      V=LAUNCH*SIN(A)
       T=0.1
9      W=ATAN(V/U)
       C=SQRT(U**2+V**2)
       X=.322*(19200*COS(A+B)-(0.1343*V+0.0269*U)*C)/WEIGHT
       Y=.322*(19200*SIN(A+B)-WEIGHT+(0.1343*U-0.0269*V)*C)/WEIGHT
       U=U+X
       V=V+Y
       IF(V.LE.0.0)GO TO 20
       IF(Y.GT.0.0)GO TO 20
       T=T+0.01
       GO TO 9
 20    WRITE(2,200)WEIGHT,JET,ANGLE,LAUNCH,T,U,V
       LAUNCH=LAUNCH+10
       IF(LAUNCH.LE.80)GO TO 5
       ANGLE=ANGLE+5
       IF(ANGLE.LE.55)GO TO 4

102       FORMAT(/)
99      JET=JET+5
       IF(JET.LE.10)GO TO 3
       WEIGHT=WEIGHT+1000
       IF(WEIGHT.LE.21500)GO TO 2

98      FORMAT(10X,'JETPIPE FIXED RELATIVE TO HORIZON',/)
100    FORMAT(10X,'WEIGHT  JET   ANGLE  LAUNCH       T     U     V')
103    FORMAT(10X,'  LBS.  DEG.   DEG.    F.S.     SEC   FT/S  FT/S')
200    FORMAT(11X,I5,3X,I2,3X,I3,3X,I5,4X,F5.1,2X,F5.1,2X,F5.2)
       STOP OK
       END

       FINISH
```

1

EFFECT OF VARYING LAUNCH ANGLES FOR VARIED JET DEFLECTIONS

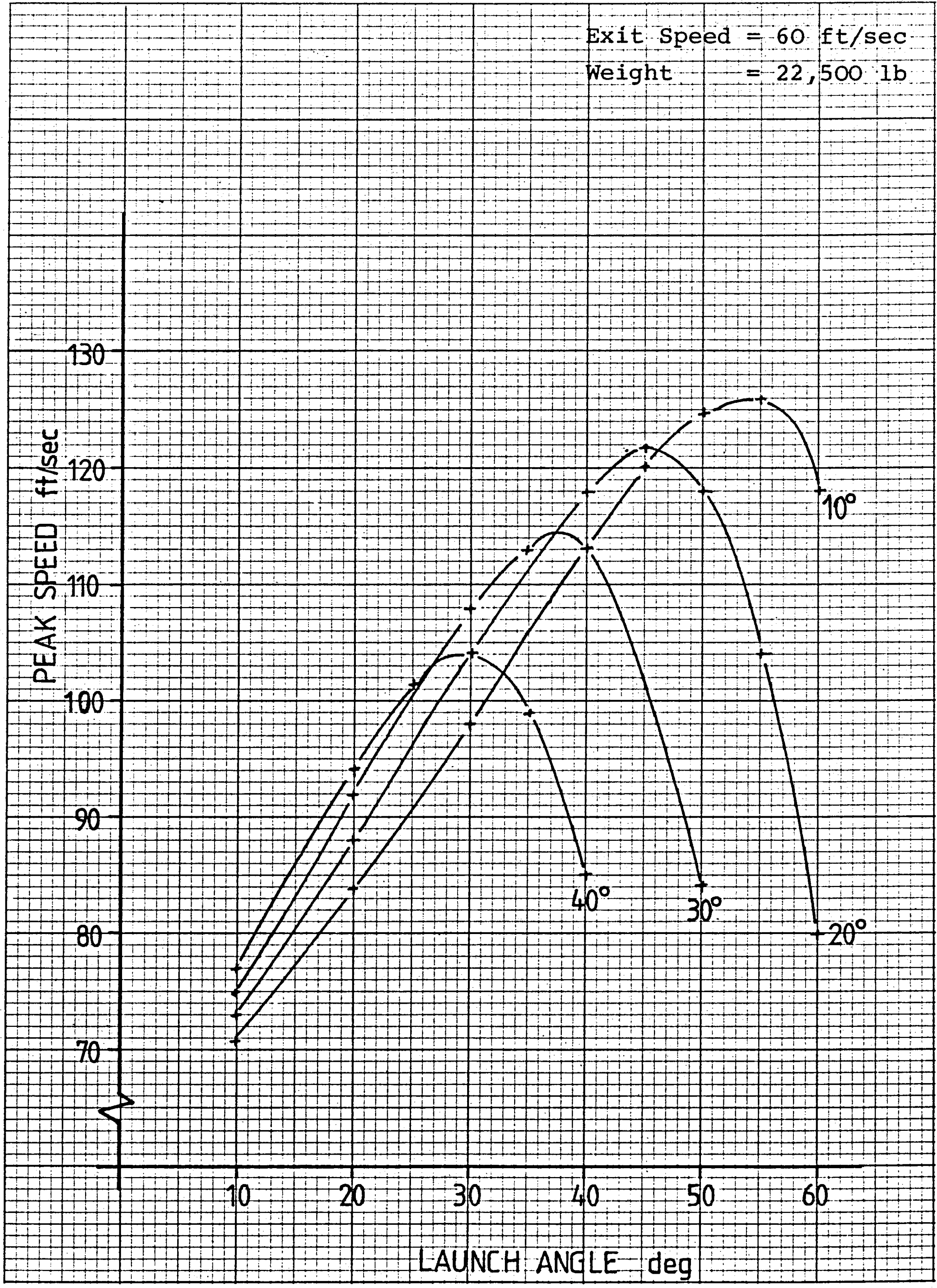


FIGURE 4.1

EFFECT OF VARYING JET DEFLECTION FOR VARYING LAUNCH ANGLES

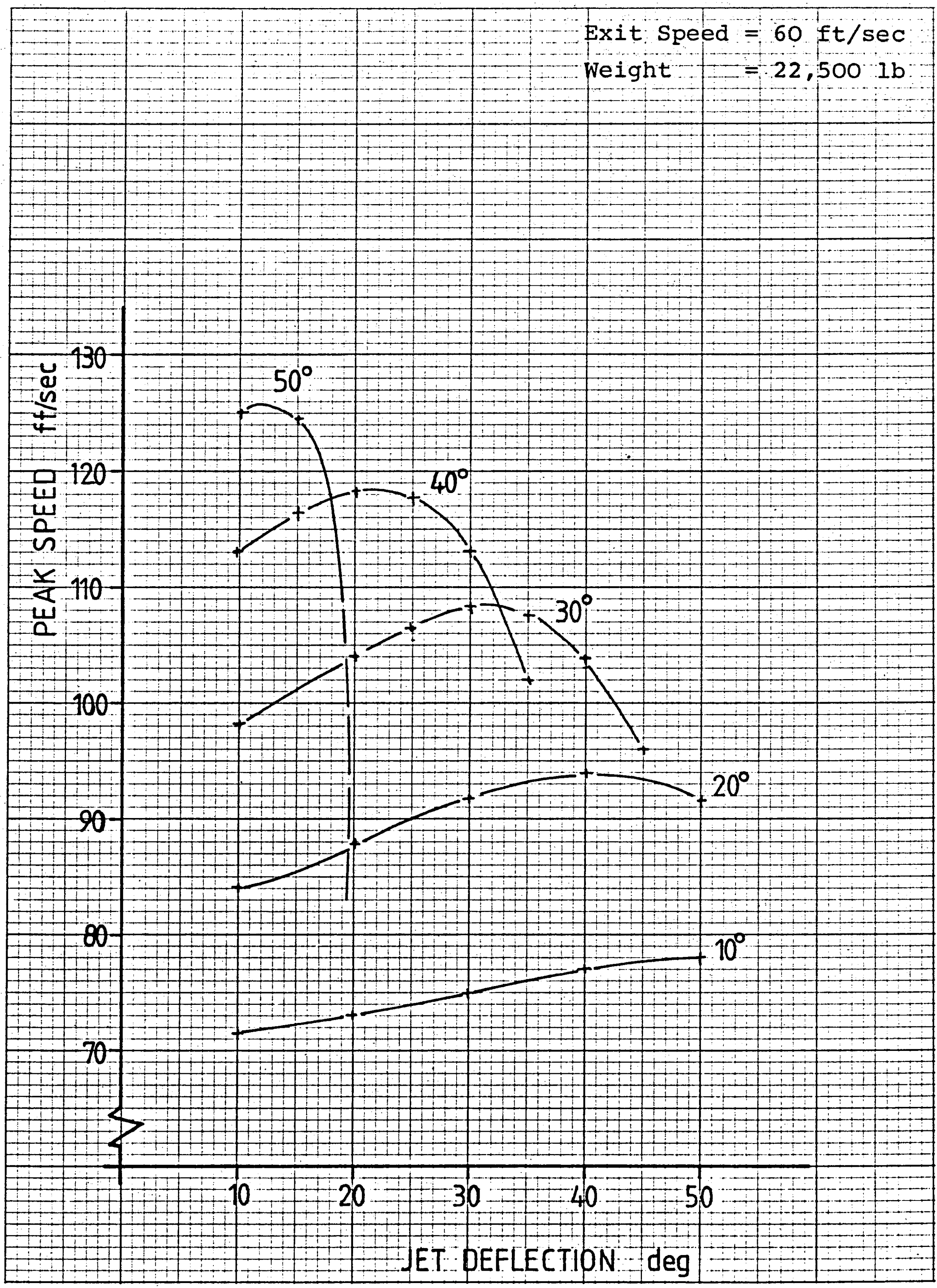


FIGURE 4.2

EFFECT OF VARYING ENDSPEEDS WITH VARIED JET DEFLECTIONS

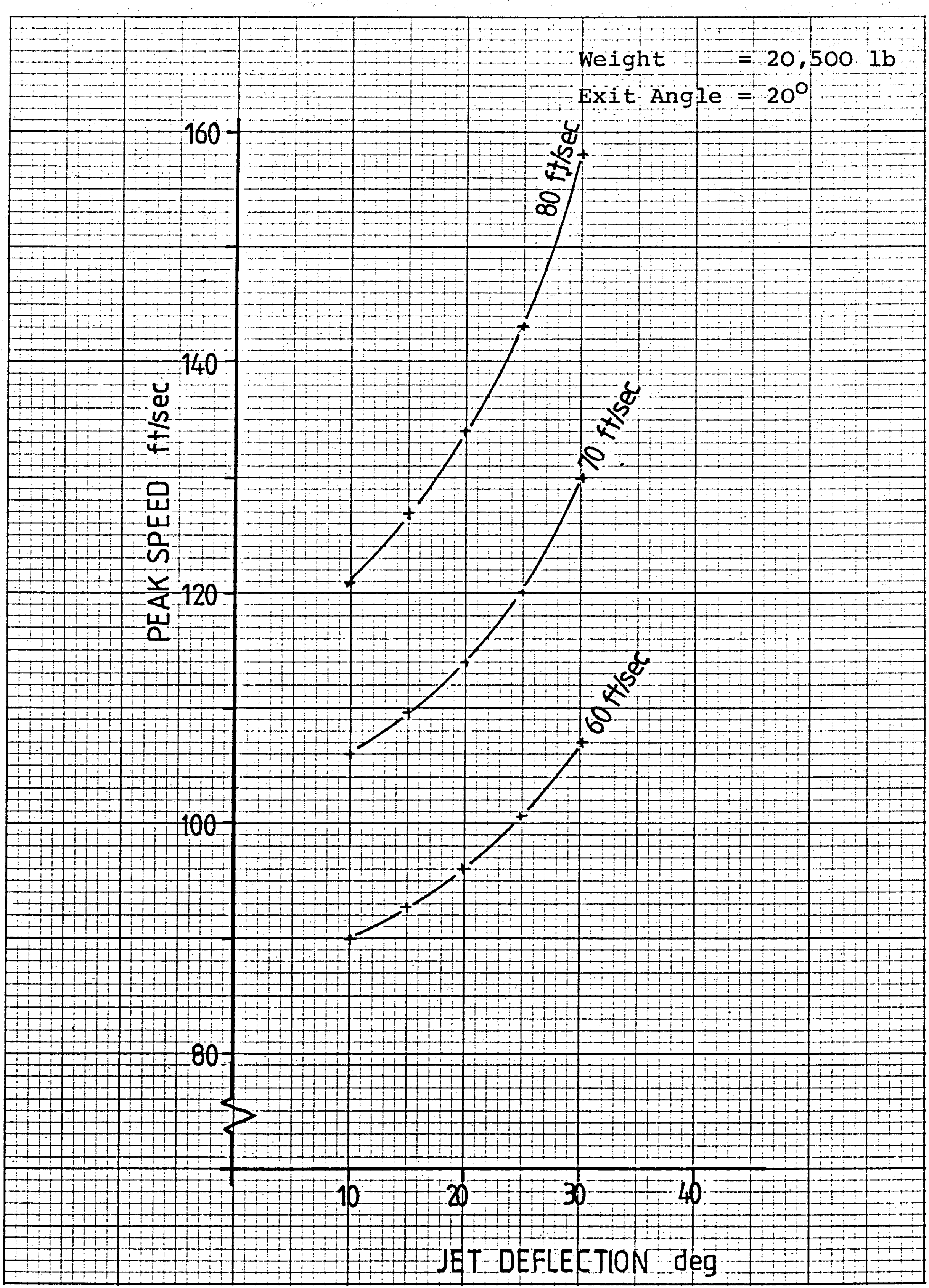


FIGURE 4.3

EFFECT OF WEIGHT VARIATIONS FOR VARIED JET DEFLECTIONS

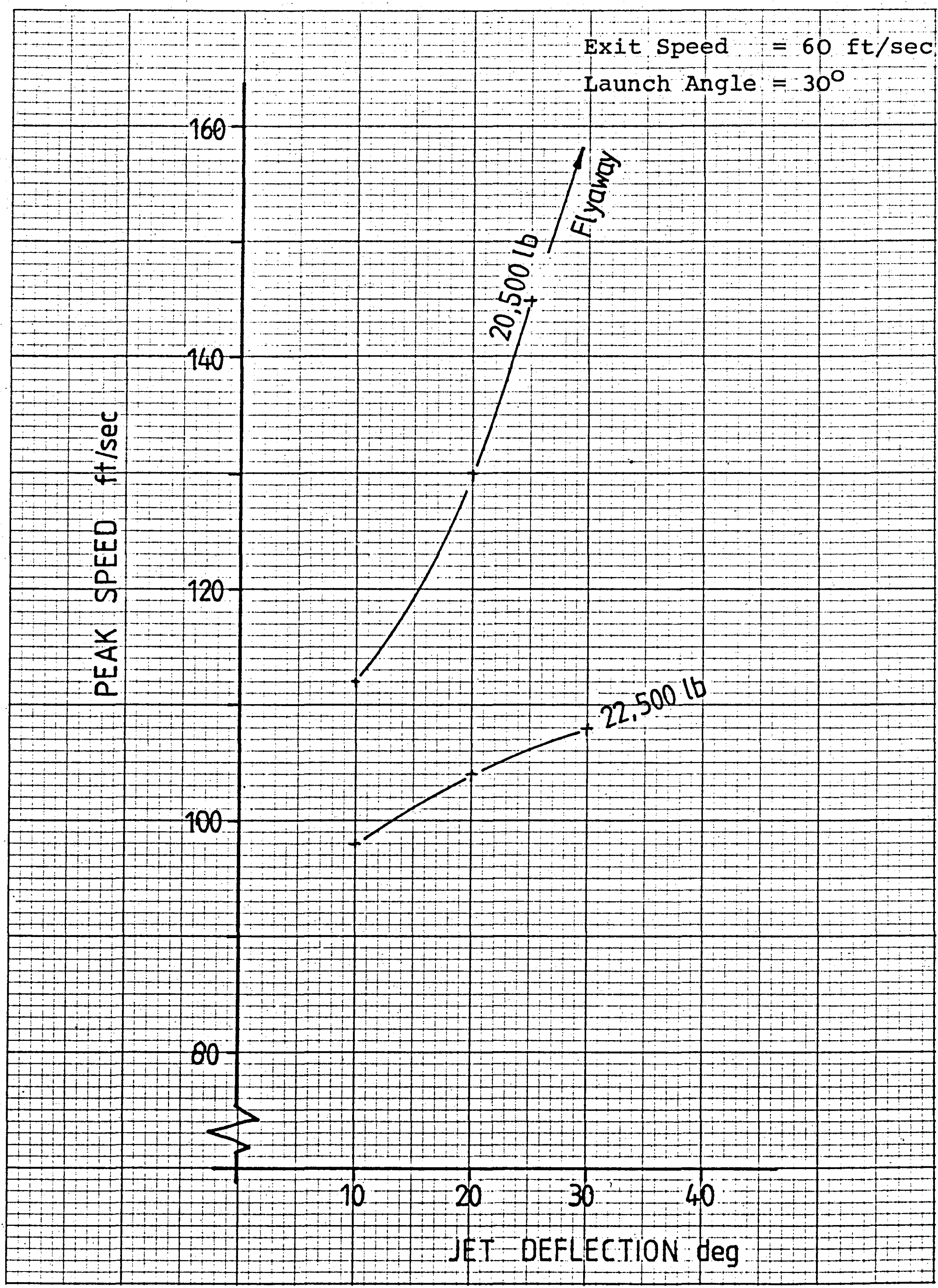


FIGURE 4.4

FLIGHT TIME TO ACHIEVE BEST PERFORMANCE

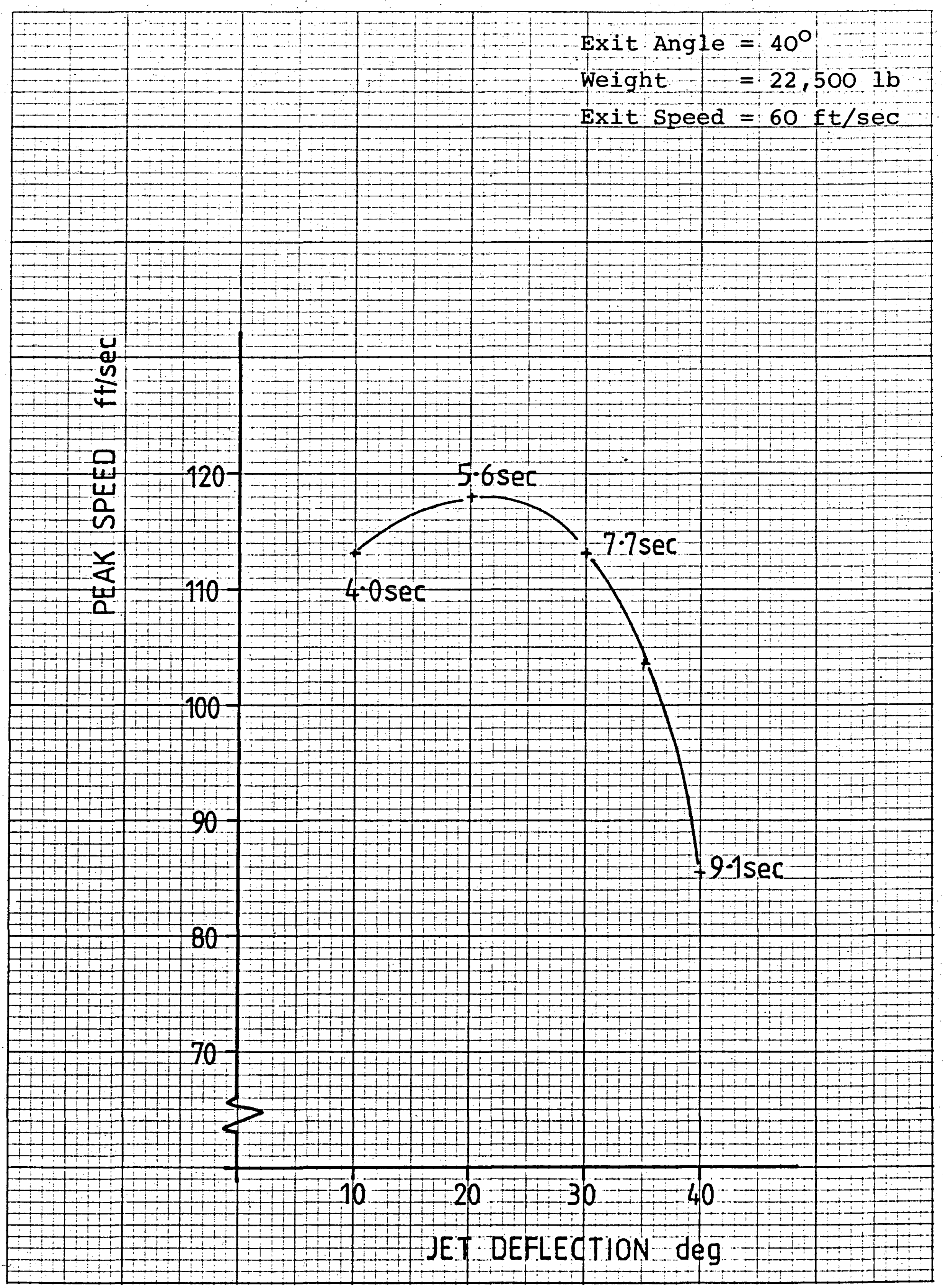


FIGURE 4.5

APPENDIX 5

LAUNCH WITH MANUAL NOZZLE SCHEDULING AFTER TAKEOFF - SKIL

In the first program, SKIJ, the nozzles are selected down to a predetermined angle before the launch is complete, and are not altered again until the aircraft is flying fast enough to permit a transition to wing-bourne flight to be initiated. At a low launch angle, say 15°, the jets can be deflected from their original 10° down through 40° or more and still leave a nett forward component. At a higher angle, say 40°, there is less room for manoeuvre if a forward acceleration is to be maintained, and not much to be gained by deflecting the jets at all. (See Figs.3.1 and 3.2). The second program, SKIK, shows there to be a bonus to be gained if the jet angle is scheduled to be constant throughout the ballistic period of flight, (see Figs.4.1 and 4.2), although this benefit is highly sensitive to small variation of launch angle and endspeed. It is of course also dependent on some mechanism being devised to cause the jet deflection angle to stay constant after launch.

So if deflecting the jets before the launch offers only a small reward and accurately scheduling them after launch offers a better one but at the cost of additional complication, the only expedient left to explore is that of resetting the jet deflection after launch. That is the purpose of this program, SKIL.

Harrier jet deflection can work at 90° per second with an acceptable degree of accuracy and overshoot. For this exercise a rate of approximately half that has been taken. Initially the jets are set at 10° to give almost maximum forward acceleration together with a small lift assistance. At a given point after launch the jets are reselected to lower to 50°, and the 40° alteration is assumed to take 1 sec at a linearly constant rate of 0.4° per 0.01 sec. This initiation point can be any time from right on launch to 3.0 seconds after launch, taken in 0.25 sec steps.

Aircraft weight is still 22500 lb, and the effects of varying the delay with a constant launch angle of 40° and launch speeds of 60, 70 and 80 ft/sec have been examined (Fig.5.1) together with the effects of varying the delay and launch angle for a constant launch speed of 80 ft/sec (Fig.5.2).

The program SKIL is at Annex 4.

ANNEX A TO APPENDIX 5

```
       LIST SKIL
     MASTER PROG
     SKIJUMP JETPIPE   DEFLECTED AFTER LAUNCH
     MAIN CALCULATION
     INTEGER WEIGHT,ANGLE
     REAL JET
     WRITE(2,98)
     WRITE(2,100)
     WRITE(2,103)
     WEIGHT=22500
     DELAY=0.0
     JET=10
     ANGLE=55   30 ,20
     LAUNCH=80   - 60,70,80
     A=ANGLE*3.1416/180.0
     U=LAUNCH*COS(A)
     V=LAUNCH*SIN(A)
     T=0.0
     W=ATAN(V/U)
     B=JET*3.1416/180.0
     C=SQRT(U**2+V**2)
     X=.322*(19200*COS(W+B)-(0.1343*V+0.0269*U)*C)/WEIGHT
     Y=.322*(19200*SIN(W+B)-WEIGHT+(0.1343*U-0.0269*V)*C)/WEIGHT
     U=U+X
     V=V+Y
     IF(V.LE.0.0)GO TO 20
     IF(Y.GT.0.0)GO TO 20
     T=T+0.01
     IF(T.GE.(DELAY+1.0))GO TO 16
     IF(T.LE.DELAY)GO TO 9
 5   JET=JET+0.4
 6   GO TO 9
 0   WRITE(2,200)WEIGHT,JET,ANGLE,LAUNCH,DELAY, T,U,V
     DELAY=DELAY+0.25
     IF(DELAY.LE.3.0)GO TO 2
98   FORMAT(3X,'JETPIPE DEFLECTED AFTER LAUNCH',/)
100  FORMAT(3X,'WEIGHT JET ANGLE  LAUNCH DELAY    T     U    V')
103  FORMAT(3X,' LB.  DEG   DEG      F.S. SEC     SEC    FT/S  FT/S')
 00  FORMAT(3X,I5,2X,F5.2,1X,I3,2X,I3,2X,F4.2,2X,F5.1,2X,F6.2,2X,F5.2)
     STOP OK
     END

     FINISH
12.55.05←
```

MANUAL JET DEFLECTION AFTER LAUNCH

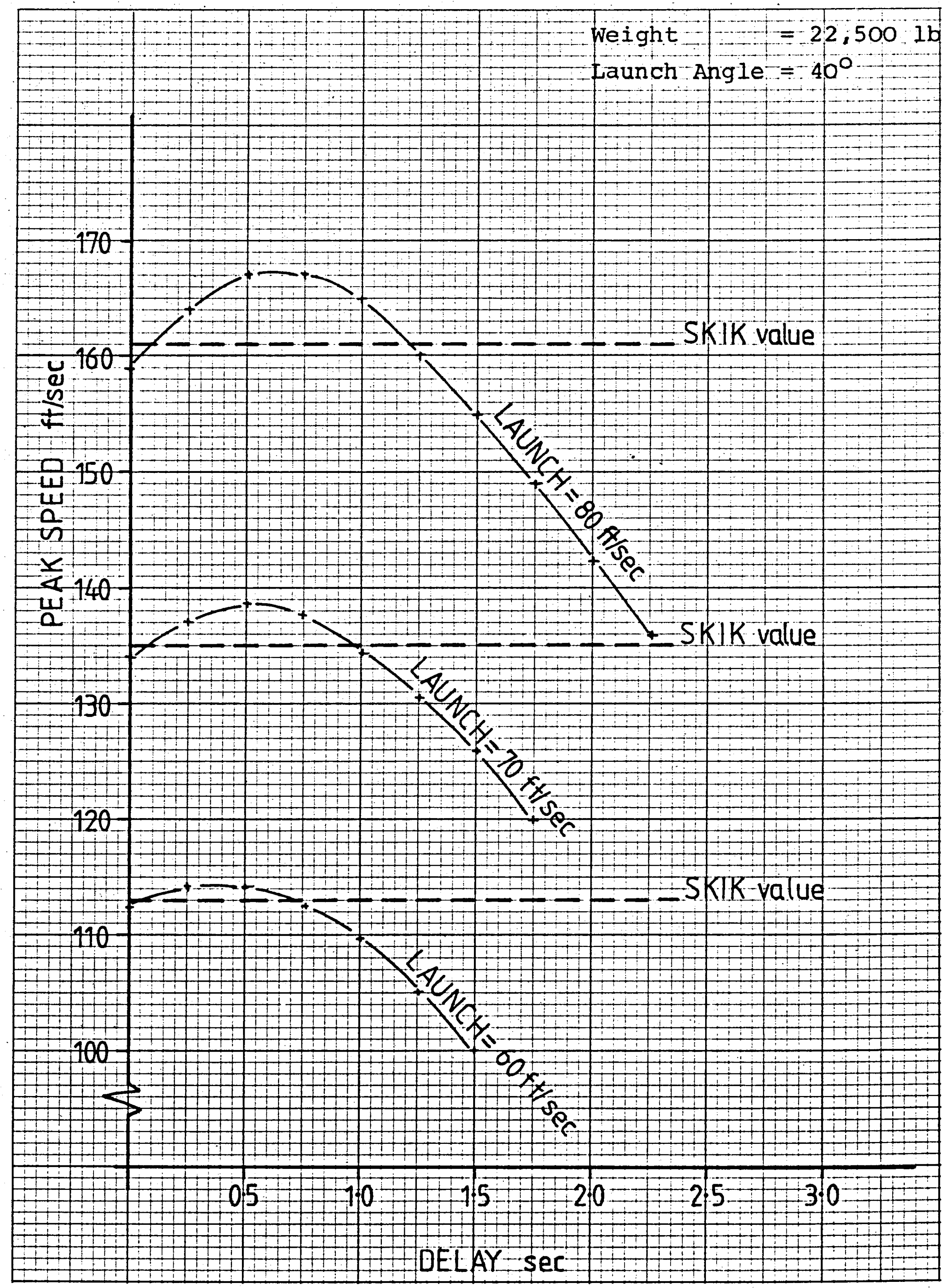


FIGURE 5.1

MANUAL JET DEFLECTION - VARYING LAUNCH ANGLE

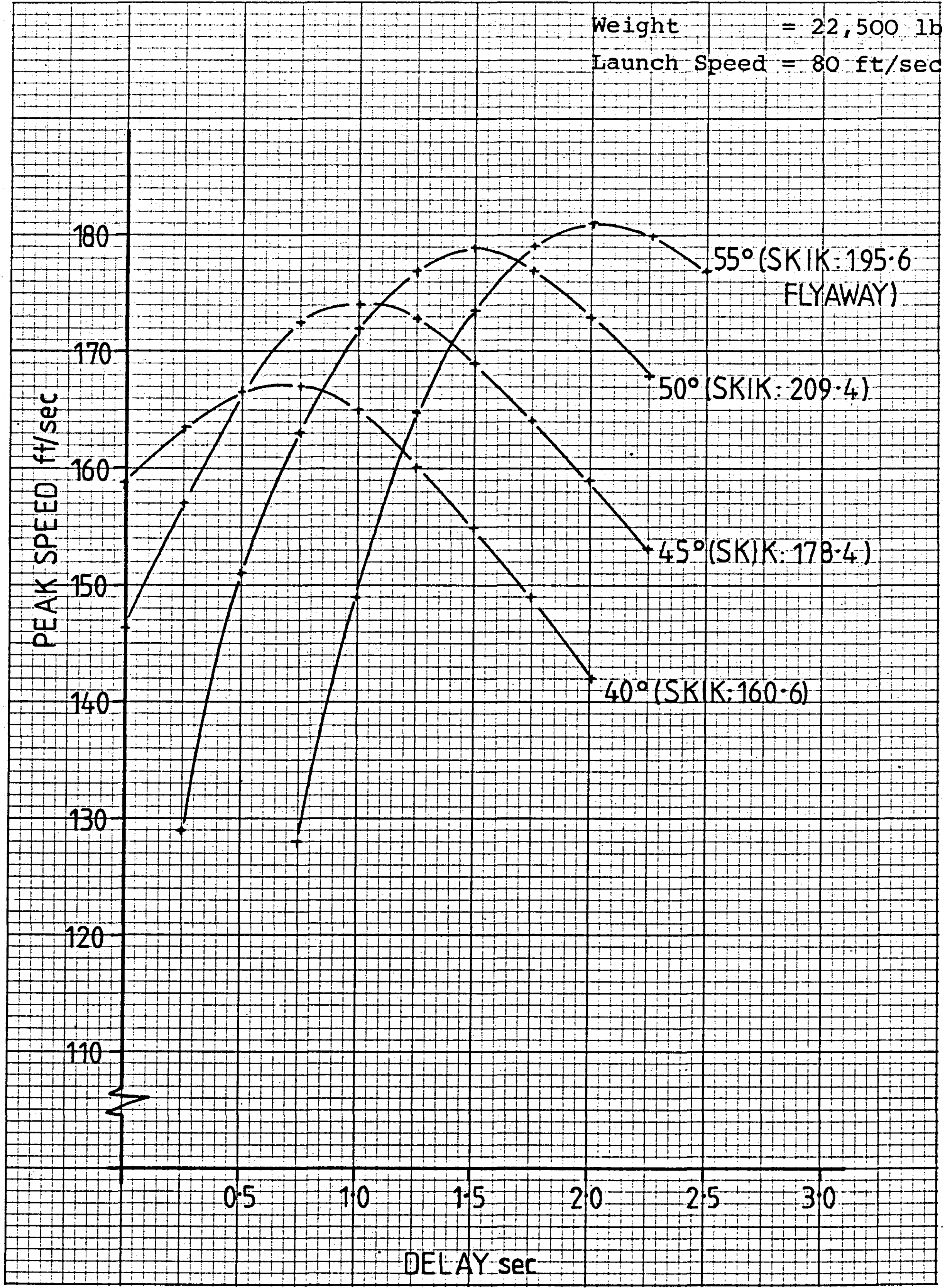


FIGURE 5.2

APPENDIX 6

COMPUTATION OF LAUNCH SPEEDS : SKIM + SKIP

1. Zero Scheduling and Automatic Scheduling

The source program SKIJ and SKIK were both amended to produce a value for the launch speed that would generate a defined flyaway condition for any set of launch parameters.

The system used was to start off with a launch speed of a deliberately low value. The vertical speed was examined after each 0.1 sec interval. If it ever fell below the required value of +5 ft/sec, the launch speed was increased by +1 ft/sec and the cycle repeated. This continued until the achievement of the first launch in which the vertical speed never fell below the +5 ft/sec criterion, and this was the speed printed.

In the event of a flyaway before the vertical velocity ever reached 5 ft/sec, as could arise from a launch at a low weight and a steep angle, printout happened as soon as the change in vertical velocity ceased to have a negative sign.

Typical results obtained from both programs are at Fig.6.1, and a family of launch speeds for typical weights and exit angles is depicted in Figs.6.2a through c.

Programs SKIM and SKIP are at Annex A and Annex B respectively.

2. Manual Scheduling After Launch

With the aim of investigating the effect of lowering the jets after launch, so that full axial acceleration could be sustained for as long as possible in the case of a free takeoff, program SKIM was amended by having spliced into it the delay scheduling loop from Program SKIL, which is described in Appendix 5.

One program, SKI1, is at Annex C. No conclusive results were reached as a result of the brief examination of the technique that was conducted, but the results of Appendix 5 give rise to optimism that there are gains available.

Such curves as were obtained are not as fluent as those others which have been produced. The reason is to be found in the relative crudity of this initial approach.

Launch speeds are in whole numbers, jet deflections are in abrupt steps of 4° at a time. If this technique is to be explored further the program will need to be refined into taking more delicate steps, and will therefore be longer, and more costly, to run.

```
           LIST SKI
        MASTER PROG
        SKIJUMP JETPIPE  FIXED RELATIVE TO AIRCRAFT
        MAIN CALCULATION
        INTEGER WEIGHT,ANGLE
        WRITE(2,98)
        WRITE(2,100)
        WRITE(2,103)
1       WEIGHT=21500
2       JET=40
3       ANGLE=40
4        LAUNCH=30
        IF((JET+ANGLE).GT.85)GOTO 77
33       CONTINUE
5       A=ANGLE*3.1416/180.0
6       B=JET*3.1416/180.0
7       U=LAUNCH*COS(A)
8       V=LAUNCH*SIN(A)
        T=0.01
        W=ATAN(V/U)
        C=SQRT(U**2+V**2)
        X=3.22*(19200*COS(W+B)-(0.1343*V+0.0269*U)*C)/WEIGHT
        Y=3.22*(19200*SIN(W+B)-WEIGHT+(0.1343*U-0.0269*V)*C)/WEIGHT
        U=U+X
        V=V+Y
        IF(V.LE.5.0)GO TO 18
        IF(Y.GT.0.0)GO TO 20
        T=T+0.1
        GO TO 9
18      LAUNCH=LAUNCH+1
19       GO TO 33
 20     WRITE(2,200)WEIGHT,JET,ANGLE,LAUNCH,T,U,V
        ANGLE=ANGLE+10
         IF(ANGLE.LE.45)GO TO 4
        WRITE(2,300)
77      JET=JET+10
        IF(JET.LE.50)GO TO 3
        WRITE(2,300)
        WEIGHT=WEIGHT+1000
        IF(WEIGHT.LE.22500)GO TO 2
98      FORMAT(10X,'JETPIPE FIXED RELATIVE TO AIRCRAFT',/)
100     FORMAT(10X,'WEIGHT  JET   ANGLE  LAUNCH       T     U     V')
103     FORMAT(10X,'  LBS.  DEG.   DEG.    F.S.      SEC   FT/S  FT/S')
 300     FORMAT(/)
200     FORMAT(11X,I5,3X,I2,3X,I3,3X,I5,4X,F5.2,2X,F5.1,2X,F5.2)
        STOP OK
        END

        FINISH
10.45.31←
```

```
        LIST SKIP
      MASTER PROG
C     SKIJUMP JETPIPE  FIXED RELATIVE TO HORIZON
C     MAIN CALCULATION
      INTEGER WEIGHT,ANGLE
      WRITE(2,98)
      WRITE(2,100)
      WRITE(2,103)
1     WEIGHT=19000
2     JET=30
3     ANGLE=20
4       AUNCH=20
        F((JET+ANGLE).GT.80)GO TO 99
33     CONTINUE
5     A=ANGLE*3.1416/180.0
6     B=JET*3.1416/180.0
7     U=LAUNCH*COS(A)
8     V=LAUNCH*SIN(A)
      T=0.01
9     W=ATAN(V/U)
      C=SQRT(U**2+V**2)
      X=3.22*(19200*COS(A+B)-(0.1343*V+0.0269*U)*C)/WEIGHT
      Y=3.22*(19200*SIN(A+B)-WEIGHT+(0.1343*U-0.0269*V)*C)/WEIGHT
      U=U+X
      V=V+Y
      IF(V.LE.5.0)GO TO 18
      IF(Y.GT.0.0)GO TO 20
      T=T+0.1
      GO TO 9
18    LAUNCH=LAUNCH+1
19     GO TO 33
 20   WRITE(2,200)WEIGHT,JET,ANGLE,LAUNCH,T,U,V
      ANGLE=ANGLE+10
       IF(ANGLE.LE.40)GO TO 4
      WRITE(2,300)
99    JET=JET+5
      IF(JET.LE.50)GO TO 3
      WRITE(2,300)
      WEIGHT=WEIGHT+1000
      IF(WEIGHT.LE.22000)GO TO 2
98    FORMAT(10X,'JETPIPE FIXED RELATIVE TO HORIZON',/)
100   FORMAT(10X,'WEIGHT  JET   ANGLE  LAUNCH      T      U     V')
103   FORMAT(10X,'  LBS.  DEG.   DEG.     F.S.     SEC    FT/S  FT/S')
 300    FORMAT(/)
200   FORMAT(11X,I5,3X,I2,3X,I3,3X,I5,4X,F5.2,2X,F5.1,2X,F5.2)
      STOP OK
      END

      FINISH
11.00.33←
```

```
      MASTER PROG
C     SKIJUMP.LAUNCH SPEEDS W.MAN.DEFLECTION
C     MAIN CALCULATION
      INTEGER WEIGHT,ANGLE
      WRITE(2,98)
      WRITE(2,100)
      WRITE(2,103)
1     WEIGHT=21000
      DELAY=0.0
3     ANGLE=40
4      LAUNCH=30
33     CONTINUE
         JET=10
      A=ANGLE*3.1416/180.0
7     U=LAUNCH*COS(A)
8     V=LAUNCH*SIN(A)
      T=0.00
9     W=ATAN(V/U)
      B=JET*3.1416/180.0
      C=SQRT(U**2+V**2)
      X=3.22*(19200*COS(W+B)-(0.1343*V+0.0269*U)*C)/WEIGHT
      Y=3.22*(19200*SIN(W+B)-WEIGHT+(0.1343*U-0.0269*V)*C)/WEIGHT
      U=U+X
      V=V+Y
      IF(V.LE.5.0)GO TO 18
      IF(Y.GT.0.0)GO TO 20
      T=T+0.1
      IF(T.GE.(DELAY+1.0))GO TO 16
      IF(T.LE.DELAY)GO TO 9
      JET=JET+4
16     GO TO 9
18    LAUNCH=LAUNCH+1
19     GO TO 33
 20   WRITE(2,200)WEIGHT,JET,ANGLE,LAUNCH, DELAY,T,U,V
      DELAY=DELAY+0.5
      IF(DELAY.LE.2.0)GO TO 3
98    FORMAT(9X,'LAUNCHSPEEDS W. MANUAL DEFLECTION',/)
100   FORMAT(3X,'WEIGHT  JET   ANGLE  LAUNCH DELAY       T      U      V')
103   FORMAT(3X,'  LBS.  DEG  DEG    F.S. SEC    SEC   FT/S  FT/S')
200   FORMAT(3X,I5,3X,I2,3X,I3,3X,I5,4X,F3.1,2X,F5.2,2X,F5.1,2X,F5.2)
      STOP OK
      END

      FINISH
14.12.31←
```

LAUNCH SPEED : SKIM

WEIGHT = 21,000 lb

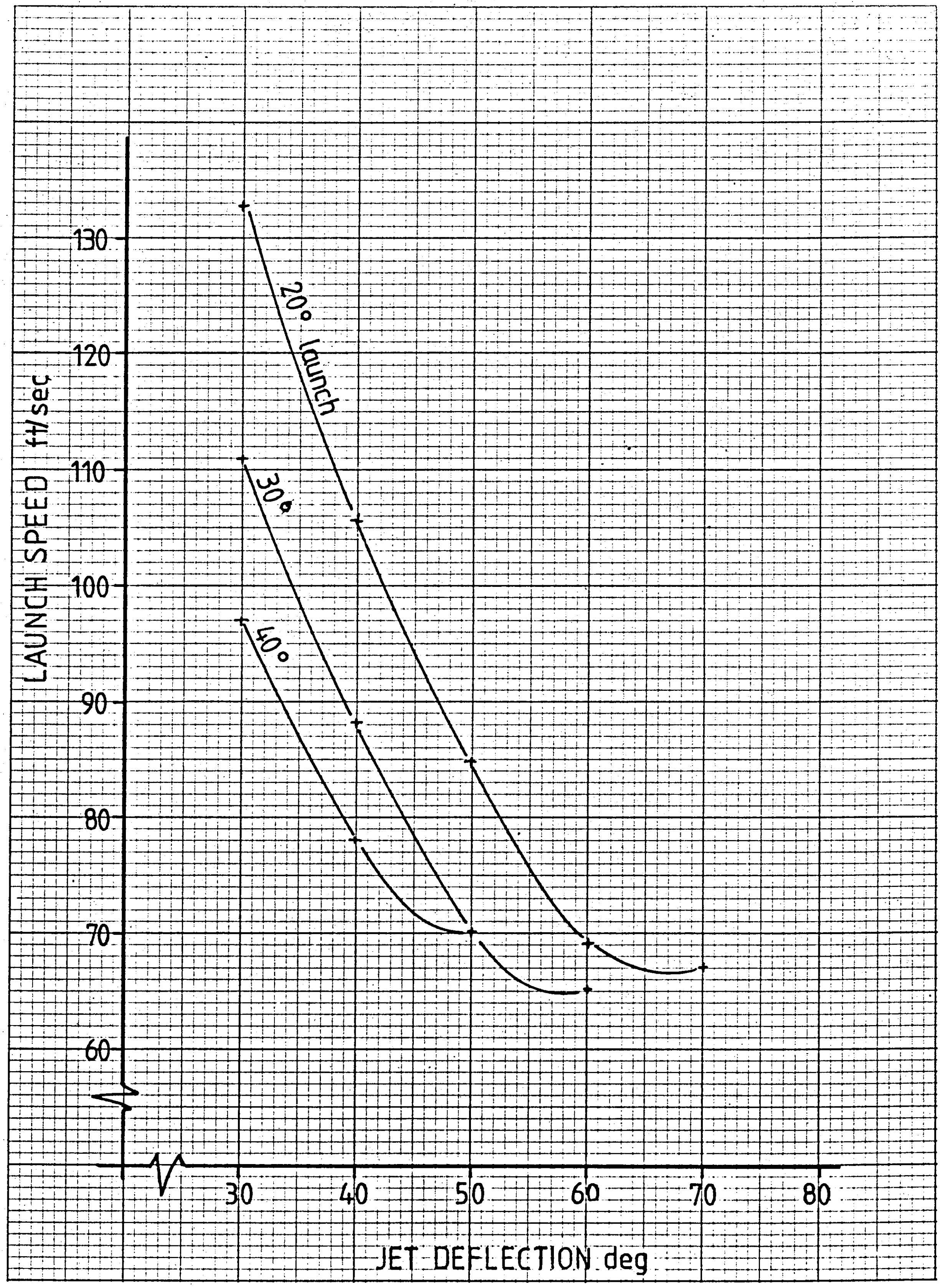


FIGURE 6.2a

APPENDIX 6

LAUNCH SPEEDS : SKIM

WEIGHT = 22,000 lb

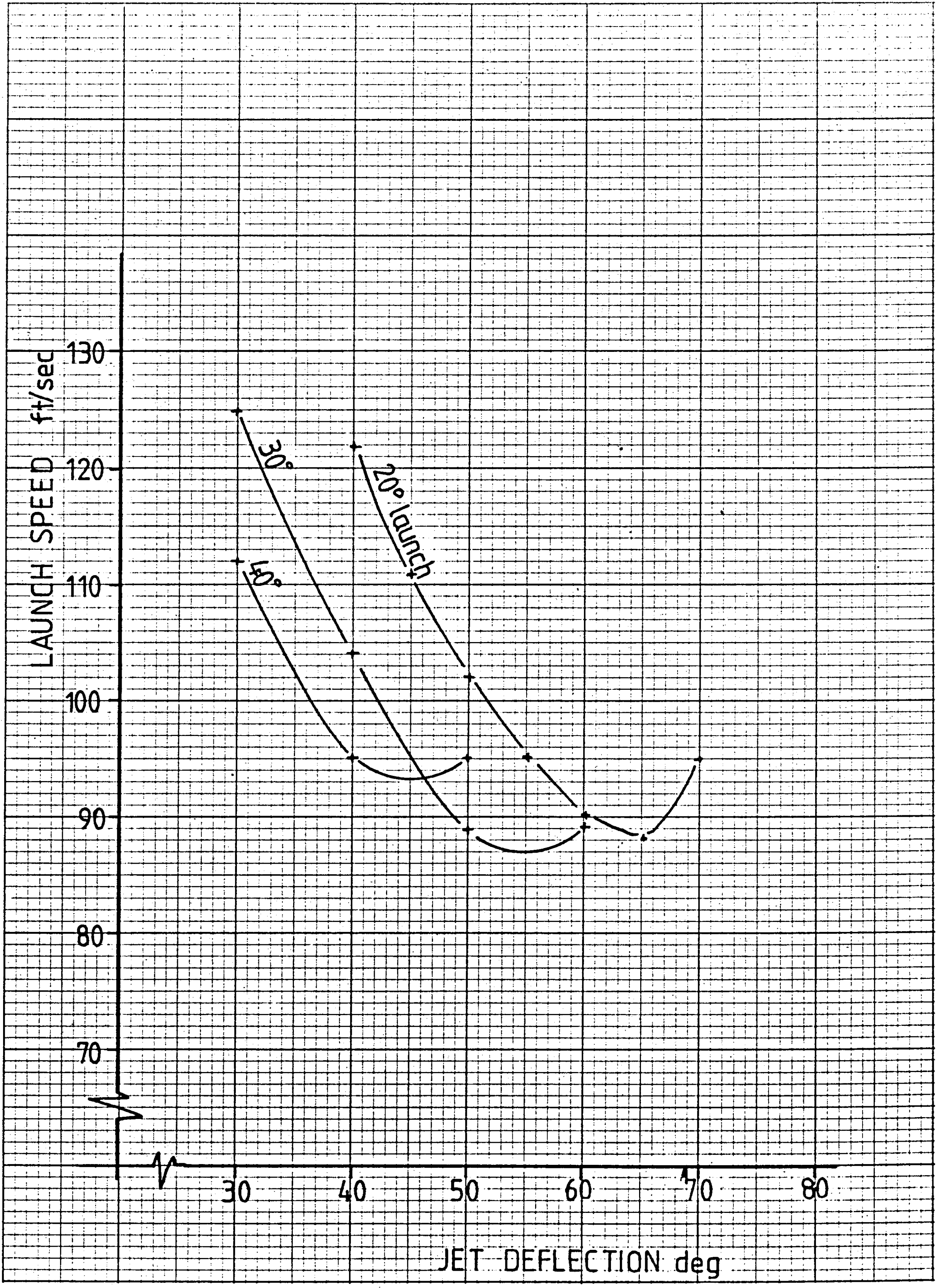


FIGURE 6.2b

LAUNCH SPEEDS : SKIM

WEIGHT = 24,000 lb

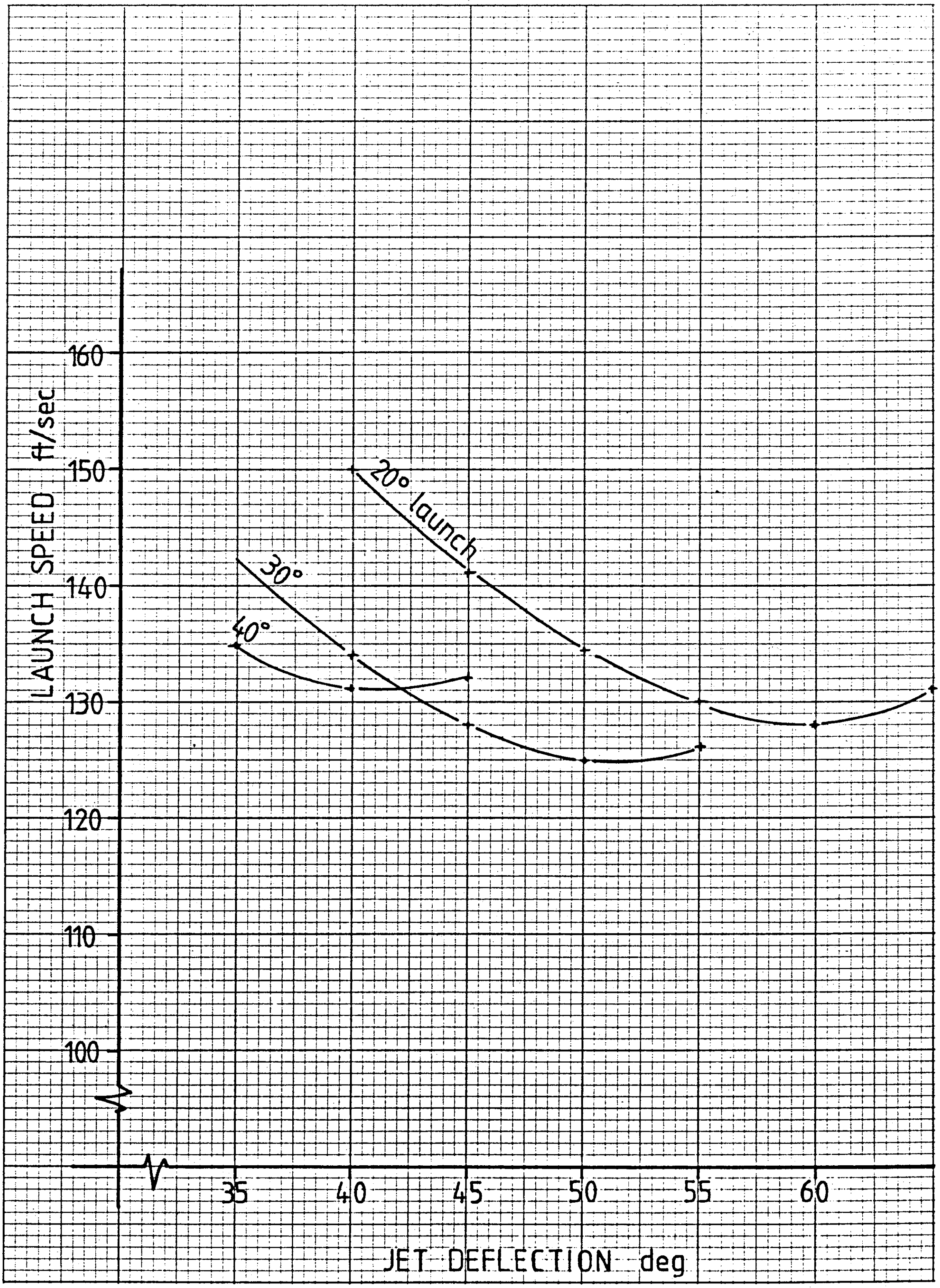


FIGURE 6.2c

LAUNCH SPEEDS : SKIM, SKIP

LAUNCH ANGLE 30°

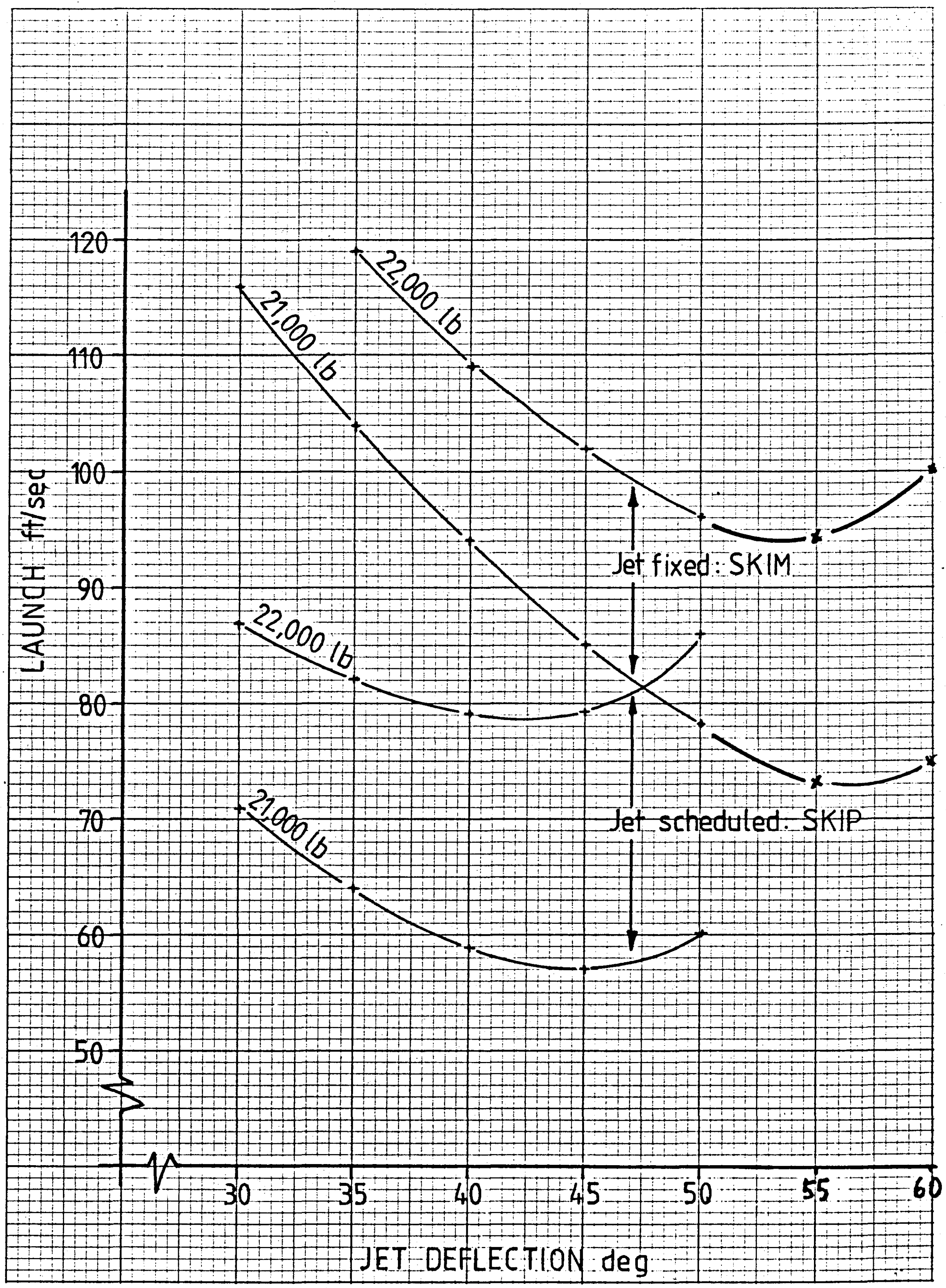


FIGURE 6.1

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Lt.Cdr.D.R.Taylor, Royal Navy
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2. 'Sea Harrier, the First of a New Wave'

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THE EMPLOYMENT OF V-STOL AIRCRAFT AT SEA

PART 3

GETTING AIRBORNE

SUMMARY

An aircraft powered by vectored thrust can be launched vertically, horizontally off a flat deck, or at an angle, using the properties of the skijump. It can fly unaided, with internal assistance as from a rocket motor, or with external launch assistance as from a catapult.

Vertical takeoff. This takes up the least space but offers the least payload of all launch methods considered. The maximum all-up weight for vertical takeoff is less than the vertical component of engine thrust due to problems of gas recirculation. These could be offset by use of a gridded deck or, better, by reconfiguration of the aircraft.

Horizontal takeoff. Performance figures for early Harrier aircraft are produced in order to offer a basis of comparison with ski-jump results.

The case for use of a holdback is discussed.

Skijump Takeoff. A method of calculating the deck run needed to reach the required takeoff speeds is described, and the adequacy of a 250ft deck with a ramp angle of 15° is demonstrated, as is the sensitivity of the performance to small degradations of engine thrust.

Rocket Assistance. Liquid and solid fuel motors are introduced, and the potential of a vectored thrust aircraft equipped with a rocket motor for added thrust at takeoff is explored. It is shown that the best employment of added thrust would be to help support the aircraft in ballistic flight than to augment its acceleration forwards.

Catapult Launching. The relatively small amount of energy required to accelerate an aircraft up to the speed required for a ballistic takeoff compared with that for a flat takeoff makes it worth looking at the low-energy catapult again. The inertia catapult is discussed together with two piston-and-cylinder catapults, one powered by compressed air and the other by a cordite charge.

Conclusions. All methods of free and assisted takeoff could have a part to play in the continuing development of the launch performance of the vectored-thrust aircraft. Not all, though, are suited to operation in a ship smaller than an aircraft carrier. Consideration of the launch methods capable of being employed in a hypothetical small ship leads to the conclusion that pure VTO and skijump are the two methods of initiating takeoff most worthy of application and development.

As soon as she had recovered her breath a little, she called out to the White King who was sitting sulkily among the ashes, 'Mind the Volcano!'

'What Volcano?' said the King looking up anxiously into the fire as if he thought that was the most likely place to find one.

'Blew-me-up,' panted the Queen, who was still a little out of breath. 'Mind you come up - the regular way - don't get blown up!'

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ANNEXES

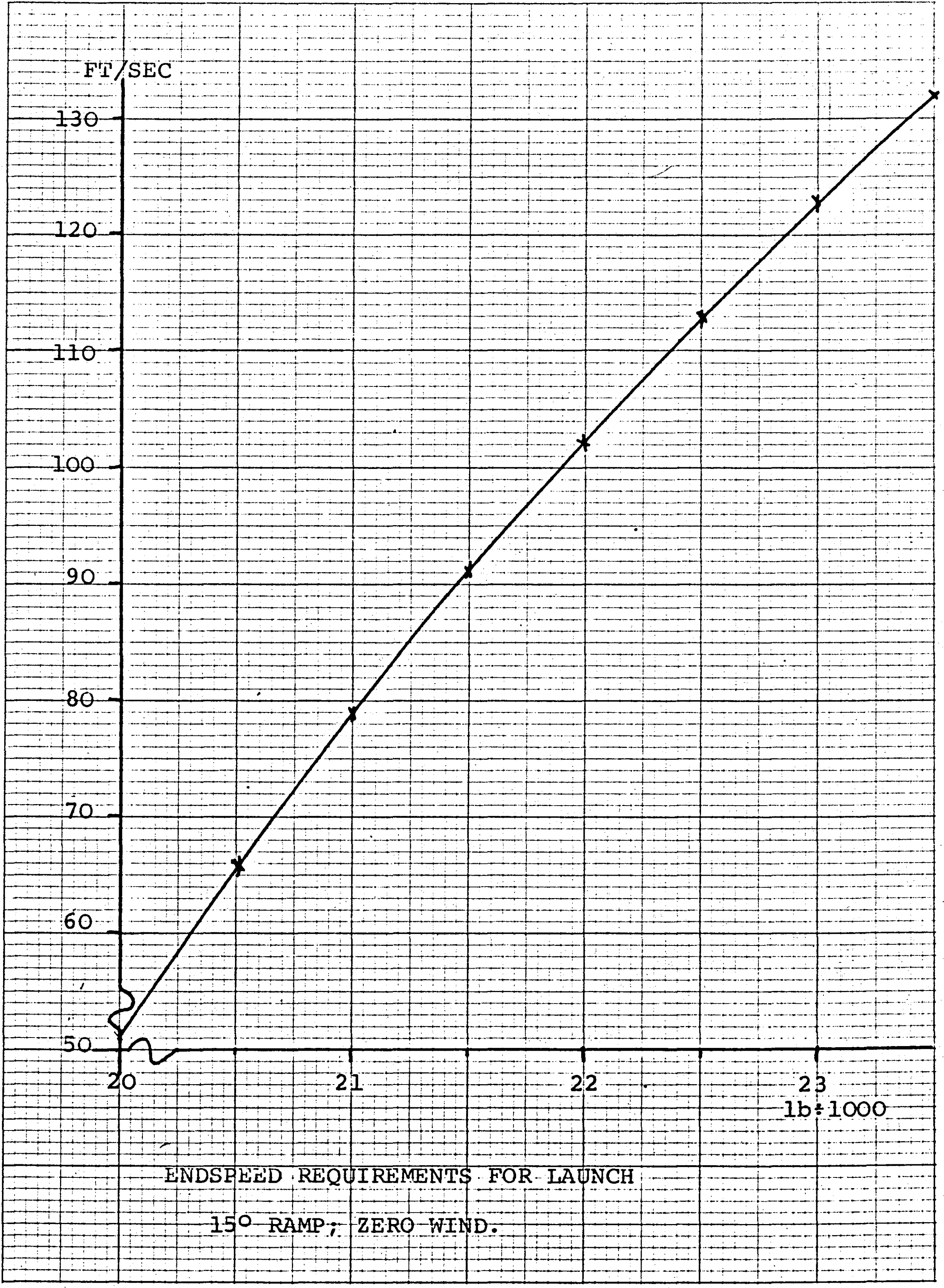
FIGURES

INTRODUCTION

The preceding part of this Study, Variations on a Theme of Skijump, introduced a method of computing aircraft performance off an inclined launch, and concluded with sets of typical values of end speeds necessary for successful flyaway conditions to be achieved over a range of representative aircraft weights and exit angles. A typical relationship between aircraft weight and endspeed required for an aircraft with the idealised performance of the Sea Harrier is shown at Fig.1.

The question now arises of how to get the aircraft airborne at all. Up to a certain limiting weight vertical takeoff is possible, and while this accomplishment is a spectacular feature of the Harrier, the performance of the aircraft can still be improved upon if an element of forward flight is introduced. Even a straight takeoff from a flat deck can be shown to be more efficient than off a runway, as the aircraft may assume a steeper flying attitude once it has left the surface. The reductions in endspeeds that a skijump launch can bring about mean that the takeoff distance can be reduced dramatically. External aids can shorten these distances even further, and assistance from both rocket motors, which as the prime movers of all our missiles are in an advanced and active state of development, and catapults, which have been designed in the past to achieve far more launch energy than the Harrier would ever need, are worth considering. Their potential contributions to increased takeoff performance should be assessed and placed on record, even if other considerations may override their suitability for use on board ship.

The values taken for engine performance and aircraft weights used in this paper are of the right order to represent the Pegasus engine in the Sea Harrier aircraft, but are intended to be typical rather than accurate, while the calculations are the Author's own. This means that the results should not be treated as if they were supported officially. Nevertheless they are substantiated well enough by the results of more exhaustive contemporary researches on the part of the manufacturers and the Royal Aircraft establishments for the order of conclusions drawn from them to be valid enough to be applicable.



ENDSPEED REQUIREMENTS FOR LAUNCH

15° RAMP; ZERO WIND.

FIGURE 1.

GETTING AIRBORNE

The Hawker P 1127, the Kestrel and the Harrier are the only vertical takeoff aircraft in the Western world ever to have demonstrated their capability to operate from the deck of a ship. The P1127 carried out its first deck trials in HMS Eagle in 1970, and at the other end of the scale the Spanish Navy operates a squadron of AV-8A Matadors at sea as a metter of routine.

If a deck run is available then it makes sense to use it for takeoff. The Harrier family while able to rise vertically from a standing start does so only at a relatively low all-up weight. The ability to carry out a rolling takeoff increases the payload considerably, and the introduction of the skijump type of launch has increased it even more for the same extent of deck space. Not surprisingly, the skijump can only be used where a flight deck length already exists, and this means that a VSTOL aircraft operating from any ship other than a form of aircraft carrier is confined to having to execute its takeoff vertically, and so incur all the penalties of weight restriction associated with such a launch.

But other aircraft have operated from ships at sea quite satisfactorily without the blessings of either long flight decks or vertical takeoff. Aviation at sea had to prove itself long before the proper flight deck made its appearance, and it did so with the aid of short flying-off decks mounted on gun houses, and then with the assistance of short-stroke catapults built into the superstructure of cruisers and heavier units of the battlefleet.

"Hermes" and "Bulwark". These are the only British flight decks at sea at the time of writing. In time they will be joined by "Invincible", and later by "Illustrious" and the fifth "Ark Royal". In the meantime, fixed-wing aviation at sea must continue. So now is the time to take another look at short-deck operation and catapult launches, and set Royal Naval aviation off on a second cycle, starting just like the first cycle with operation from non-dedicated ships, 70 years ago.

Methods of Takeoff

In this paper the methods of takeoff considered are four in number as follows:

Vertical takeoff
Short takeoff, including skijump
Rocket assisted takeoff
Catapult takeoff

Of all the advantages of the skijump, the one that mattered most to the world of the constructors and the dockyards was that it can be fitted to an existing ship with a minimum of adaptation. Particularly important is that a skijump can be built onto a ship without the necessity for the existing deck to be cut out at all. This means that no strength has been taken out of the structure so no strength need be built in to replace it. Such would not be the case if, say, a catapult had to be installed with its track at deck level. The design might not take long to finalise. But execution of the alteration and addition to enough ships of the same class to make the innovation practicable and effective might easily take 5 years or so.

This consideration must always be to the fore when investigating the possibilities of adapting an existing type of ship for the operation of VSTOL aircraft, and equally so when working on the design of a ship yet to come. Any innovations discussed in what follows have been chosen with a view to their suitability for ready and non-disruptive incorporation into the ships concerned.

METHODS OF TAKEOFF

1. VERTICAL TAKEOFF

In ideal theory a vertical takeoff aircraft can get airborne at an All-Up Weight only slightly less than the value of the engine thrust (In truly ideal theory the two can be equal in which case the aircraft sits on the deck at full power in a state of blissful equilibrium until it burns off enough fuel for the margin of thrust developed over weight to be large enough to lift it slowly, gracefully and exponentially into the sky).

In practice, there must be a margin of at least 10%, more likely 15% by which the thrust must exceed the weight for a practicable vertical takeoff to be achieved. The reasons for this are as follows:

a) The margin must be adequate for a reasonable rate of vertical acceleration to be achieved

b) The engine must develop not only power for lift but also for control; whether by thrust vectoring or by reactor jets is immaterial

c) A certain amount of jet efflux is bound to find its way into the intakes and so degrade the performance of the engine to a level below its best.

d) There will be suckdown effects brought about by entrained air in the downwash of the jets to be overcome.

Factors a and b are inevitable, but maybe there is something that can be done to reduce the losses due to factors c and d.

The Harrier has an operating weight of about 12,500lb a net thrust of about 19200 lb, and a VTO weight of about 17000 lb.

So its payload for VTO is about 4500 lb. If the T/W ratio for clean vertical takeoff is 1.05, the maximum VTO weight could be about 18350 lb, and the payload could be 5850 lb. The differences between this and the actual VTO payload of 4500 lb is therefore accounted for by the losses due to exhaust reingestion and suckdown. If these could be eliminated the VTO payload could increase by about 1350 lb or 30%. Even if they could be reduced by half in their intensity the increase in payload of 670 lb would be worth striving for.

The major problem with the Harrier in vertical takeoff is that of intake ingestion of hot gases. If the temperature at the intake is allowed to rise due to the capture of exhaust fountains then thrust is lost at the rate of 3% per 10^{O}F temperature rise (Ref.1).

While the effects of reingestion from the front nozzles are not too serious while those nozzles are cold, it can be expected that the problems would be much worse if front nozzle Plenium Chamber Burning were in use. Losses due to suckdown effects are understood to be of much less significance, So hot gas ingestion must be cut down.

Methods of Reducing Hot Gas Ingestion

Three methods are available for reducing hot gas ingestion. One requires modification to the aircraft, one requires modification to the ship, and one requires slight modification to both, coupled with a major modification to the launch manoeuvre.

Aircraft Modification

Rising hot gas fountains can be discouraged from entering the intakes if a suitable barrier is fitted. Trials are known to be proceeding with extensions to the wing root leading edge (Fig.2) LERX, which have this effect. Shaping the underside of the AV-8B to exercise some control over the exhaust gases has had the effect of lowering the intake temperature by 20^{O} and generating a lift improvement of 1200 lb. (Also see Pt 7).

Ship Modification

The jet efflux will not necessarily always go back into the intake if it can be encouraged to go somewhere else. Brochures on sea-borne Harriers dating back to 1970 have regularly depicted the aircraft operating from an area of deck formed on a grid so that the jet efflux passes through and exhausts either straight overboard if the grid forms a flight deck extension as an outrigger, or into a ventilated chamber below the grid if the grid forms part of the flight deck itself. Both these systems suffer from the disadvantage that they require modification to the ship itself.

However, researches are showing (Ref.2) that a full through-flow grid is not necessarily essential for the required attention on the jet efflux to be achieved. It can be accepted that there will be a certain penalty to be paid for setting up a VTO hover over a flat flight deck. It is quite possible that some shape other than flat could offer some improvement - certainly it is unreasonable to suppose that flat is the best shape there is and that any other surface will be even worse. Fountains are caused by a normal rebound from a flat surface. If the surface is other than flat, the rebound will be in some direction other than normal, and if an easier escape path is offered to the jet

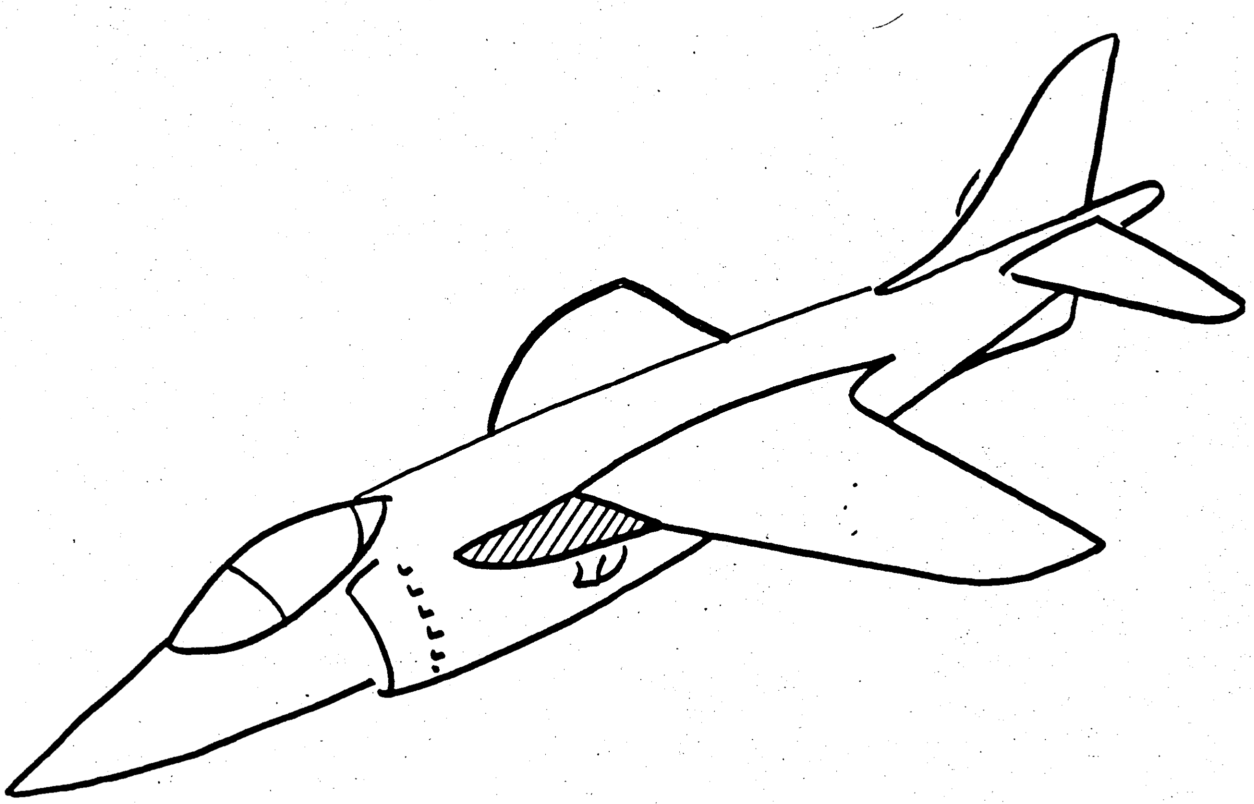


FIGURE 2. SITING OF LEADING EDGE EXTENSIONS

efflux it will surely take it. Even simple channelling orientated in any direction will have some effect. One possible solution is illustrated in Fig. 3 taken from Ref.3. Another would be to position on the deck an array of slats forming a superimposed range of channels. These would be erect at the time of takeoff, hover and landing, but could be collapsed after the manner of a venetian blind, to permit aircraft movement around the deck to take place. Both these devices fulfil the requirement stated earlier that they could be added to the flight deck of an existing ship with the very minimum of structural alteration.

A different approach to the fountain problem has been to adopt the principle of "If you can't beat 'em, join 'em". In Ref.3 is described an experiment in which a model was hovered over a surface which was deliberately configured to reverse the jet flow and use it to derive augmented lift below the aircraft. In one configuration the total upward force on the model was augmented by a factor of 2.4 and at the same time the stability in roll, pitch and yaw was improved. While such a system if developed for a full-sized aircraft would not be suitable for a high-wing aircraft like the Harrier, it nevertheless is worth bearing in mind when considering some aircraft of the future.

Manoeuvre Modification

The height to which hot gases rise will depend on ambient air conditions in general and the rate at which cold air is induced downwards by the jets in particular. As the detrimental effect of fountains falls off with height, then the higher theplacing of the intakes, the greater will be the thrust remaining on takeoff.

This simple fact is exploited in a novel manner by the technique devised for takeoff for the conceptual Northrop aircraft submissions illustrated in Part 1 Fig.7. (Ref.5). Takeoff is accomplished in two stages. First, under the influence of the front nozzles alone the aircraft is rotated to an altitude of 20^{o} nose-up in pitch with its main wheels still on the deck. Now, with the intakes some 12' - 15' clear of the deck, and effectively free of recirculating exhaust gases, liftoff is achieved by simultaneously applying full thrust and directing both nozzles perpendicular to the ground. Some form of main wheel constraint, such as chocks, might be necessary to prevent forward or aft movement during the rotated stage, but it is not considered to be essential. It is envisaged that the same procedure would be applicable to short takeoff operations by allowing full use of wing/canard lift at high angles of attack in addition to propulsive lift.

Two features of the Harrier prevent such a procedure being followed at present. One is that the fore and aft nozzles are not controlled individually and the other is

EXHAUST GAS CONTROL PLATFORM

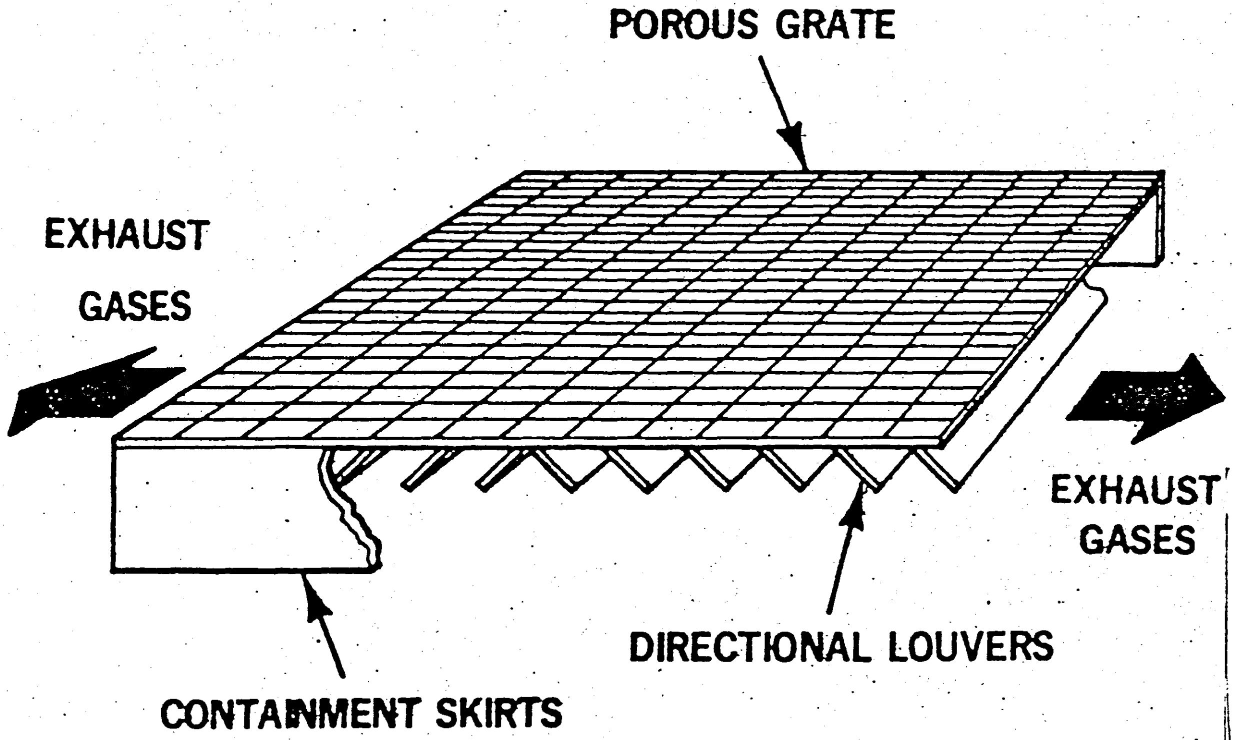


FIGURE 3

that rotation to a high nose-up attitude is limited by the presence of the ventral fin and the fact that the axis of the outriggers runs behind the axis of the main wheels. Here is another design consideration to be remembered when the successor to the Sea Harrier is in the course of being schemed.

2. SHORT TAKEOFF

In the present context, "short takeoff" means 'very short indeed' compared with the length of flight-deck run with which the fixed-wing operator is usually familiar, even when talking about the Harrier.

Before the inclined ballistic launch came into prominence, flight deck trials of the Harrier were little more than embarked exercises to confirm the short takeoff performance ashore.

Typical figures were (Ref.6)

Harrier Mk.1, All-Up Weight of 19000 lb

Pegasus Mk 101, Thrust of 15200 lb

Required launch EAS = 114 knots (= 190 ft/sec)
Required deck run = 530 ft.

In fact the shortest run capable of being read from the graph of Airspeed versus Distance and Weight in Fig.2 of Ref.6 is 200 ft.

An aircraft rolling forward under a thrust force equal to its weight will accelerate as if it were in a state of free fall. After only 100 ft it will be doing nearly 80 ft/sec, another 50 ft brings its speed up to over 95 ft/sec and as has been demonstrated in Part 2, this sort of speed is all that is needed for a successful ballistic launch.

A run of 150 ft might not be too hard to come by in some types of ship not currently considered in the role of Aircraft Carrier. If a short-flight deck is to be created where none was before, it must be ensured that every foot has to be used to its fullest advantage.

The Holdback

In the free takeoff calculations in Reference 6, the technique used is for the engine to be accelerated with the nozzles fully aft and for the aircraft to start rolling when the brakes can no longer hold it, that is when the engine speed runs up through about 50% rpm N_H. As the aircraft moves forward the engine is still accelerating and the thrust is still increasing, all this while ground is being covered. This will not be acceptable for an ultra-short takeoff, as this further acceleration phase can take as long as 5 seconds. Therefore some form of mechanical holdback capable of restraining the aircraft during full power checks and capable then of bring released by either the pilot or the Flight Deck Officer must be introduced into the system. To quote once more from Ref 6:

"It should be noted that a holdback which would allow the deck run to commence with full thrust would reduce the distance for a given speed by 63 ft".

In 63 ft an aircraft accelerating at 1g can reach a speed of 63 ft/sec.

Two other considerations militate strongly in favour of a holdback:

a. That in a free takeoff without a holdback the pilot will not know his engine has developed full power until he has travelled a fair distance down the deck, and the more reluctant the engine is to accelerate the more deck space he will consume.

b. That at present some engines are known to stagnate at an N_H of 94%, even though the acceleration has been satisfactory up to that point. A full-power run while the aircraft is held at a standstill is the only way of assuring the pilot that his engine is capable of performing satisfactorily during the takeoff.

There remains, however, one argument in favour of a swift run up and departure rather than carrying out a protracted run at full power whilst remaining effectively tethered. The j.p.t. limiters in the Harrier have a time delay of about 10 seconds. This is allowable because maximum takeoff rpm can be held for that length of time before the corresponding turbine inlet temperatures have established themselves well enough to damage the fabric of the structure. After about 10 seconds at maximum takeoff rpm, the limiters will become effective, and if conditions merit it, they will signal for a reduction in rpm to be made. This leads to the possibility of a reduction in thrust during the climb out.

On balance, though, a holdback is essential for a short takeoff. On the subject of holdback operation, a further study on Harrier operations from aircraft carriers (Ref.7) recommends as follows:

"The use of a pilot-operated holdback is considered preferable to a deck officer-operated system as the pilot, when carrying out a free takeoff, must take immediate steps to control the aircraft, directionally on release, a situation which does not occur in catapult launches. He is unlikely to do this as effectively if the release is under the control of a deck officer, particularly in the presence of significant deck motion.

Operationally, a holdback would appear to offer significant savings in the launch cycle time. The holdback could be fitted to the aircraft before engine start and automatic loading into the deck fixture could be achieved, thus eliminating manual loading delays. Aircraft weight penalties are not necessarily significant as the release mechanism could remain part of the holdback, operation being achieved from the aricraft electrics using a snap connector".

Although those comments were meant to apply to operations from what used to be a conventional flight deck, they are still just as relevant to the consideration of single-aircraft operation from the deck of a sub-capital ship.

SKIJUMP TAKEOFF

The subject of how to achieve short takeoffs from a flat deck is covered in References 6 and 7, and as has been noted already the length of the deck runs considered has always been at least 200 ft and is generally of the order of 400 ft or more.

Clearly, now that the skijump is known and established, there is no point in considering flat takeoffs any further. What needs to be looked into now is the question of how compact a skijump can be usefully installed in a ship smaller than an aircraft carrier.

Skijump Analysis

For the purposes of analysis, the skijump can be considered as consisting of two distinct parts. First there is a flat run-up, then the curve from the cusp of which the aircraft takes off. As the parameter which matters most is the endspeed, these two parts will be considered in reverse order.

Rolling Acceleration

In considering rolling acceleration up to end speeds of the order with which we are concerned at present it is acceptable to ignore forces due to aerodynamic drag and base all calculations on an assumption of constant acceleration.

The excuse for making this convenient simplification is offered in Annex A, and further substantiation is found in a paper published in 'Journal of Aircraft' 1968 (Ref.8).

In this paper it is shown that if the acceleration of a STOL aircraft varies by less than 40% between the time it starts rolling and the time it gets to the end of its ground run, the difference between the ground run calculated on a basis of Acceleration = $K_1-K_2V^2$ and that assuming acceleration to be constant, is only 2.3%. This felicitous discovery is applied throughout this part of the Paper as giving an acceptable approximation.

Acceleration round a curve

The object here is to find what speed an aircraft must have reached by the foot of the curve of the skijump for it to be able to reach the required exit speed at the top. Calculation of this speed, or indeed of the speed anywhere round the curve is made complicated by the cycle of events by which acceleration increases speed, speed increases centripetal force, centripetal force increases friction drag and increased friction drag works against acceleration. As in the Taylor thesis a simple iterative process is used to calculate the start speed and this is described in Annex B, together with a worked example. Also in Annex B is a comparison between speed achieved around a curve and the speed achievable along the flat projection of that curve from which an adequate approximation to the former can be made.

Examples and results

1. Aircraft weight 20,000 lb; skijump angle 20^{o}, radius 180ft:-
Thrust 19200 lb.

a. Exit speed required = 75 ft
Entry speed required = 48 ft/sec (Annex B)

b. Distance to 48 ft/sec = 41.3 ft (Annex A)

c. Projected length of skijump = $180^{o}\sin 20^{o}$
= 61.5 ft

To this must be added an 11 ft straight section at the exit to stop the aircraft rotation in pitch and another 30 ft or so to accommodate the aircraft and anchor the holdback.

Total length ≈ 150 ft

2. Useable deck 250 ft; skijump 15^{o}; wind over deck 20 knot;
Engine thrust : on deck 17000 lb ± 800 lb
in flight 19200lb ± 800 lb

Results:
Worst case : Aircraft weight = 22500 lb
Average case : Aircraft weight = 23300 lb
Best case : Aircraft weight = 24300 lb

These latter results show the sort of figures that a ship with 250ft of useable deck run, i.e. 280 or so overall might achieve in favourable wind conditions. The sensitivity to thrust variations is discussed below.

Skijump Performance

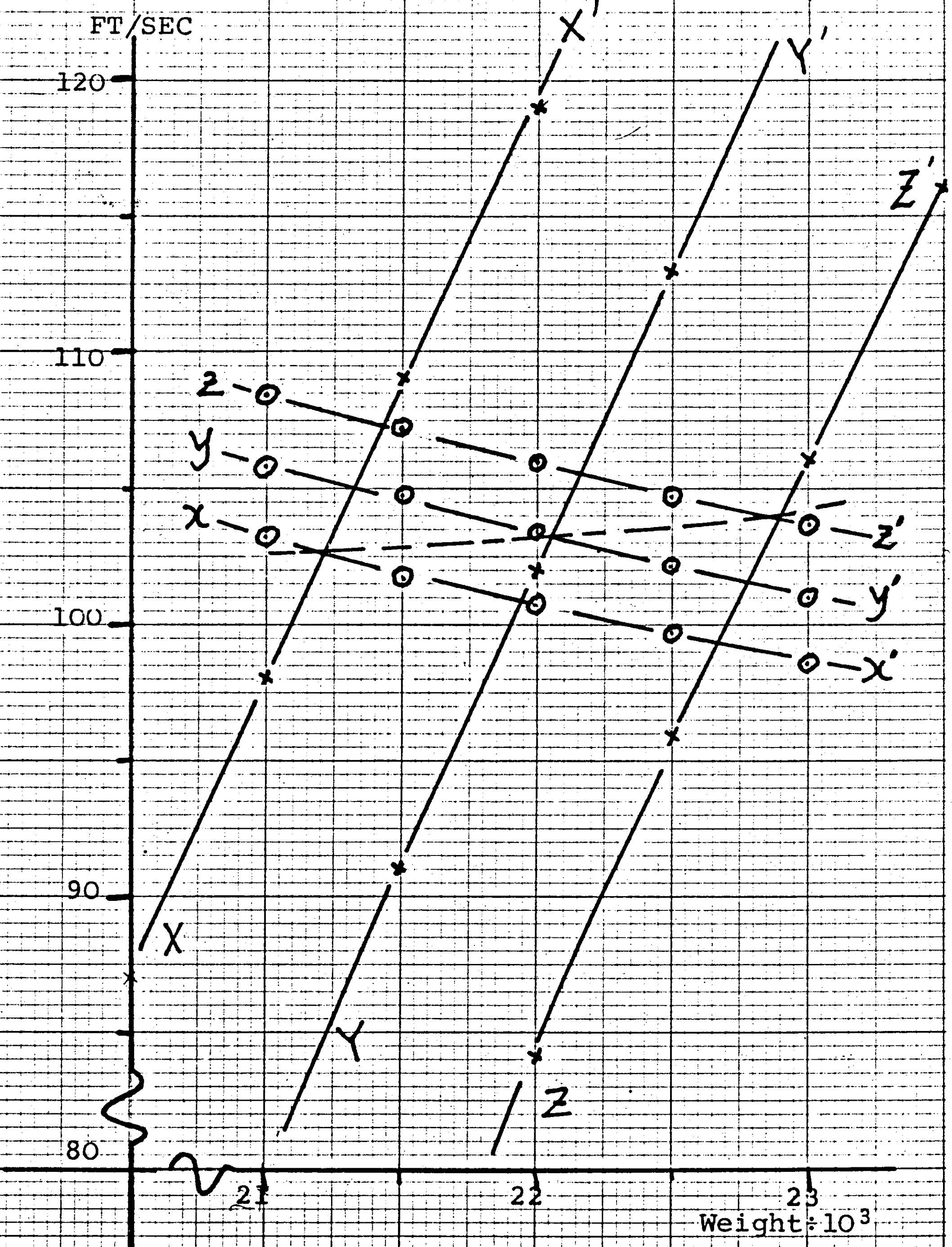
It was shown at the end of the previous part of this paper that the value of the end speed required for a safe launch at a given weight is particularly sensitive to small variations in the engine thrust available. If the standard thrust of 19,200 lb decreases by only 800 lb, the decrease associated with a drop of 1% N rpm, the required end speed goes up by 18 ft/sec. The effect a similar variation in thrust has on the length of takeoff run to achieve a given end speed is far less.

This is illustrated in Fig.4. Lines XX', YY' and ZZ' represent the endspeed/weight relationships for launch from a 15° skijump in still air and correspond to thrusts of 18,400 lb, 19,200 lb and 20,000 lb respectively. Lines xx', yy' and zz' show the corresponding end speeds achieved at the end of a deck run of 250 ft, using the method of calculation described in Annex B.

The intersections of matched pairs of lines represent the maximum launch weights for each set of circumstances. What is of particular interest here is not just the range of absolute values of launch weight, (21,200 lb, 22,050 lb and 22,900 lb respectively), but the differences in spacing of the two sets of lines. The spaces between lines xx', yy' and zz' show the gains in endspeed that a little extra thrust can provide. They are very small compared with the differences between lines XX', YY' and ZZ' which show the reduction in end speeds required that the same little extra thrust can achieve.

A small increment of thrust confers very little advantage while the aircraft is accelerating along the deck. For any length of deck the end velocity is a function of the square root of the thrust, so a small variation in thrust is not expected to have much effect. Once the aircraft is off the deck however, with the jets deflected downwards and the extra thrust contributing to the support of the weight, it is a different matter entirely. A thrust increment now is rewarded by a matching increment in launch weight.

This has two main implications. The first is the obvious one that the higher the Thrust/Weight ratio of the aircraft the higher is the weight at which it can be launched. The second is that if auxiliary thrust were available from some extra source of power it would be much more effective if deployed in the lifting direction than in the acceleration direction. This will be illustrated



LAUNCH ENDSPEEDS FOR 15° SKIJUMP
AND SPEEDS AT END OF 250' DECK; ZERO WIND

FIGURE 4

when rocket assistance is discussed a few pages hence. A further implication, returning for a moment to the jpt limiter, is that this could be allowed to be effective during the run up to full available power and also during the takeoff run without much detriment to the length of that run. The extra thrust made available by, in effect, overriding it, would be much more welcome and useful if it were employed once the nozzles go down at the end of the deck and the ballistic flight phase begins.

Accomodation

Given now a means of determining the endspeed required for a skijump launch, (Part 2, Program SKIM), and also a method of calculating the deck run necessary to achieve that endspeed, (Annex A and B), it is now possible to combine these two in order to find out how long a deck is necessary for the full performance of the aircraft to be able to be exploited.

First the program SKIM was run, choosing a typical value of Thrust of 20,000 lb and a range of launch weights from 20,000 lb to 25,000 lb in steps of 500 lb, a fixed nozzle angle of 55° and an exit angle of 15°, (neither of which latter values is optimal). This produced a set of values of endspeed.

Then the length of deck run required to reach each endspeed was calculated using the methods described in Annex A and B, and the calculations repeated for the endspeeds corrected for wind-over-deck speeds of 15 knots and 30 knots.

These calculations are shown in Annex D.

The results are shown in Figs.4a, 4b and 4c, and demonstrate the capacity of the skijump to permit launches at aircraft weights well over those for vertical takeoff.

It has been shown in Part 2 (Fig.2) that this simple model, in use is capable of producing results very close to the real thing for the ranges of values considered so it is reasonable to infer that the conditions depicted in Figs.4a, 4b and 4c are also a fair representation of the performance to be expected from a skijump in practice. The implications of the curves are that given a deck run of the order of 250ft, aircraft at launch weights lower than those corresponding to the points of intersection with the deck length could launch from the full deck at less than full power, (or use a reduced deck run at higher power), while launches at the maximum all-up weight are possible given sufficient headwind.

While the results obtained by this method are offered with no great pretensions as to their precision, they are nevertheless considered good enough to be used as a basis for comparisons when other methods of launching are reviewed.

While a stretch of 250 ft is much shorter than a conventional flight deck, such a distance is not going to be found easily on an existing vessel. Thus it is that designs for "Harrier Carriers" have been submitted to the Royal Navy, while the US Navy is considering a possible conversion scheme from a standard DD 963 destroyer into an air capable ship. The before-and-after profile of such a ship is shown in Fig.5 taken from Ref.9.

Possible scope for development in the field of compact launch installations is offered by the Three Rail Skijump currently being considered by British Aerospace. This is a variation on the standard skijump in which the elevated deck is replaced by a structure of three rails, a central one offering a track for the aircraft nose and main wheels and the outside ones supporting the outriggers.

The wheels on the central track are supported in dollies of some sort, thus it is possible that a track radius of less than 150 ft could be used. This would mean that the possibility of an exit at greater than 20° could be reconsidered, together with all the advantages that it can offer.

A three-rail skijump offers a tempting possibility of being used as a semi-permanent installation, maybe in outrigger or bowsprit form, as well as a deck installation as on a flat-topped 'non-commissioned' ship. It is tempting too to be drawn to the idea of a monorail skijump capable of being extended from the ship when required and retracted again after use. Unfortunately discussions have confirmed that all three rails are definitely necessary. Unlike a glider that can support itself in roll very early on in a winch or aerotow launch, a Harrier, once allowed to roll at such an early stage of a launch as its run up a skijump would be unlikely to recover. Full use of aileron/reaction control would serve only to rob the engine compressor of more bleed air than it could possibly spare at such a critical point in the takeoff.

The skijump takeoff then will be restricted to ships able to offer a clear run of at least 250 ft. Such ships can be built, vide the 'Harrier-Carrier' proposals, or converted from existing designs, as in the American DD 963. Should a conversion be contemplated, then a three rail skijump, with its obvious advantages of being a lighter and less permanent structure than a full-deck skijump has a lot to offer.

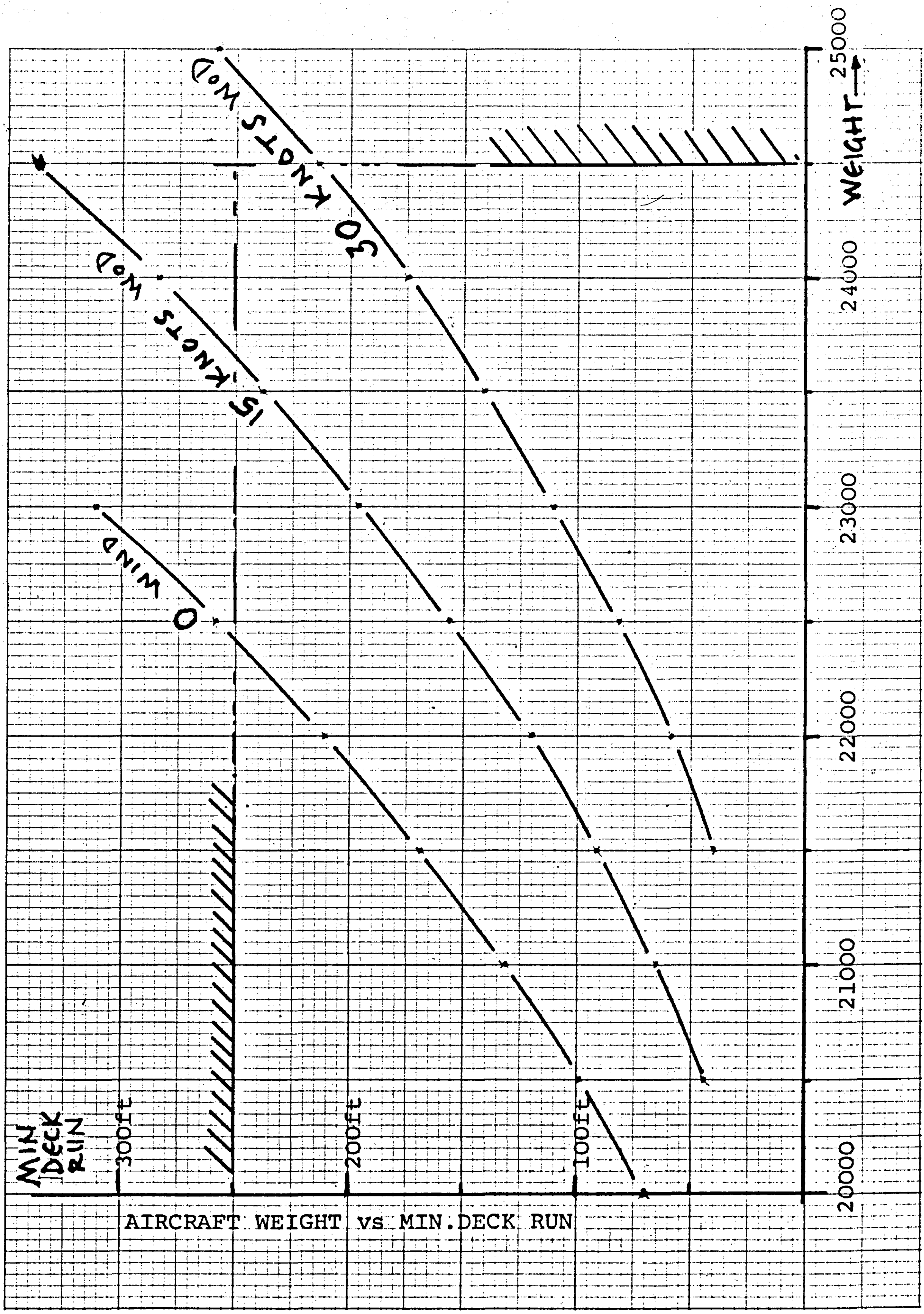
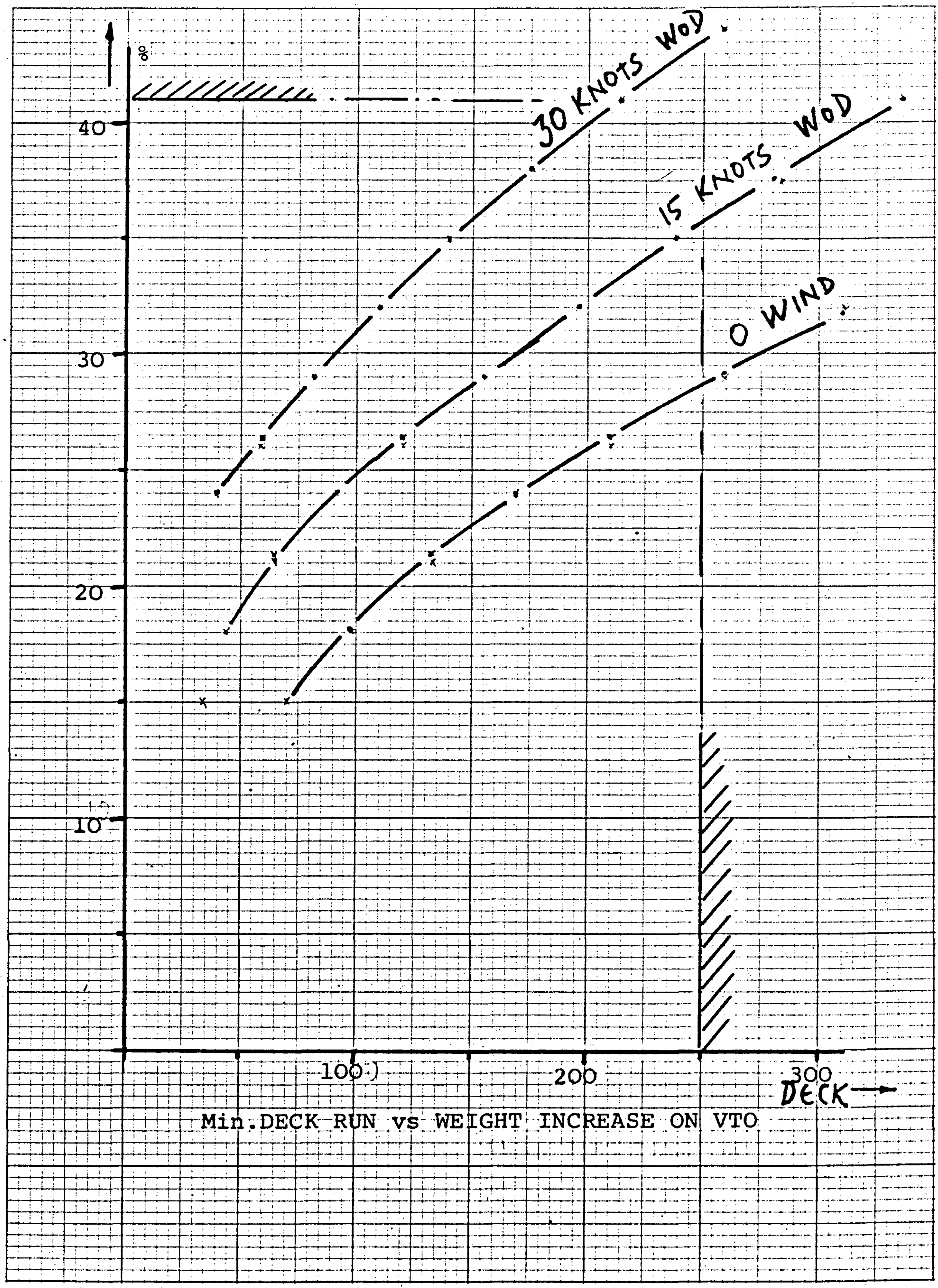
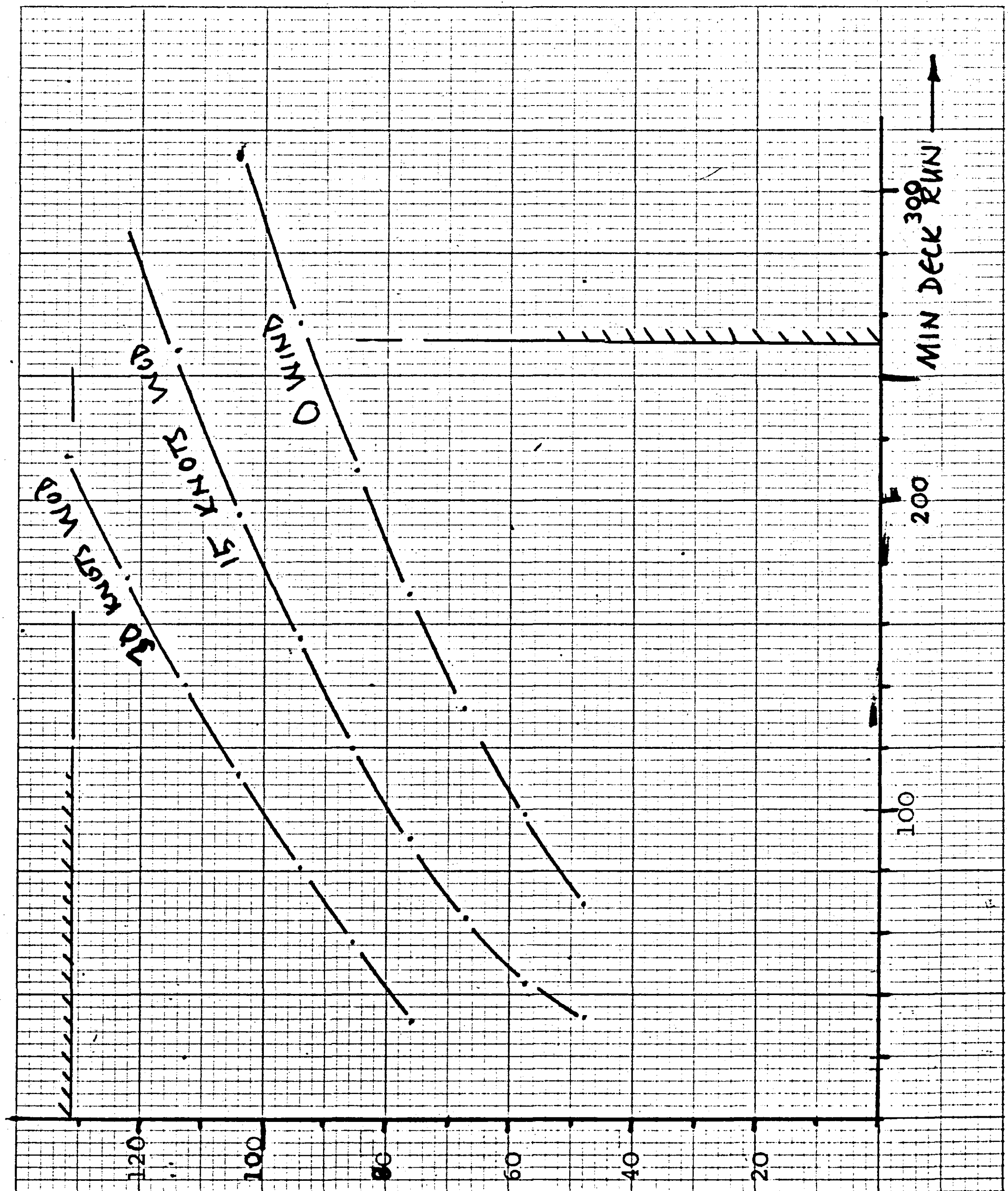

30 KNOTS WOD
15 KNOTS WOD
0 WIND
WEIGHT ⟶
25000
24000
23000
22000
21000
20000
MIN DECK RUN
300ft
200ft
100ft
AIRCRAFT WEIGHT vs MIN.DECK RUN

FIGURE 4a



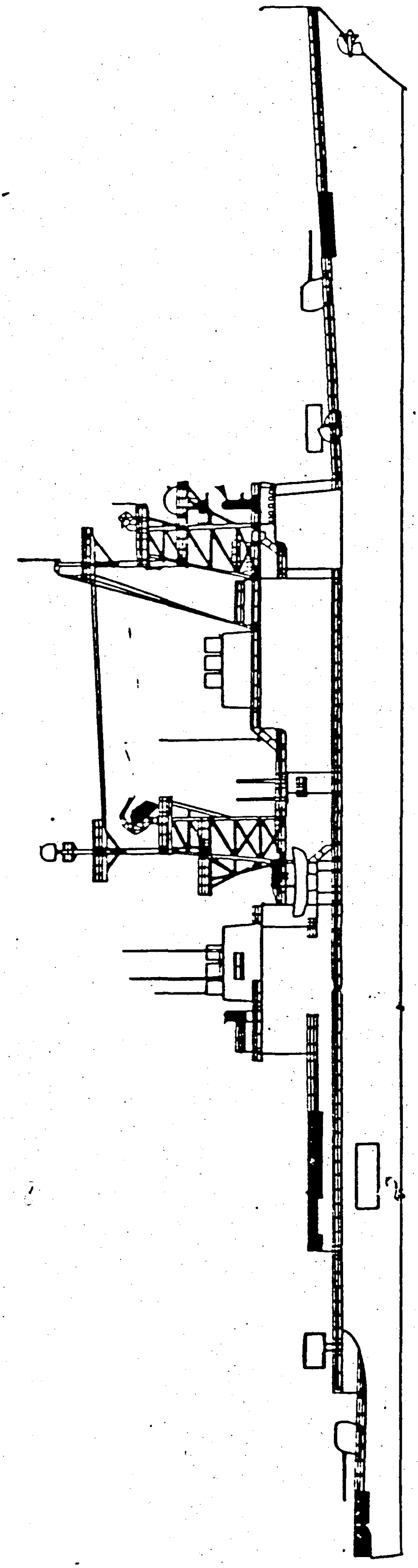
Min.DECK RUN vs WEIGHT INCREASE ON VTO

FIGURE 4b

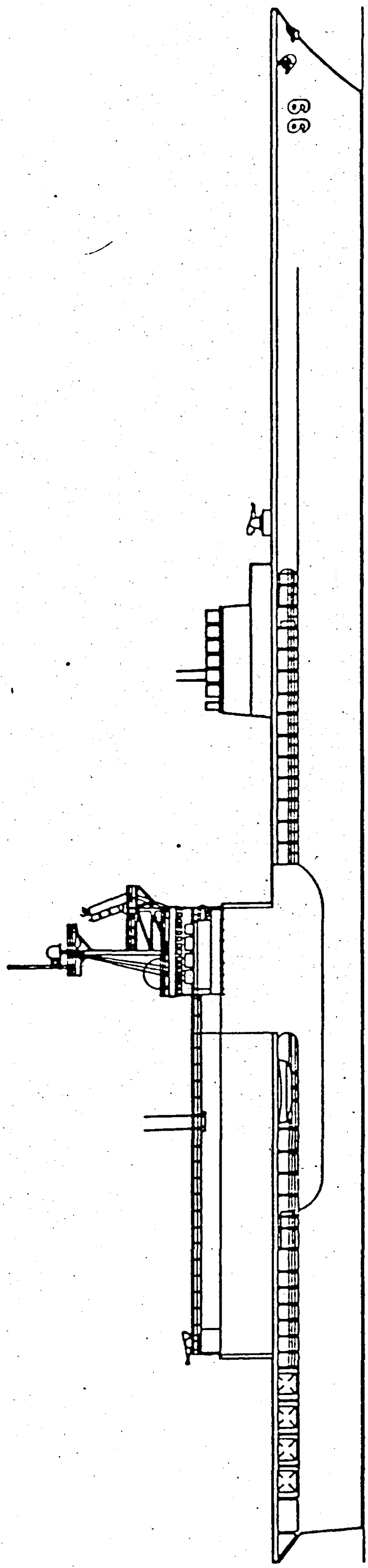


MIN.DECK RUN vs PAYLOAD INCREASE OVER VTO

FIGURE 4c



IN PRODUCTION DD 963



DESIGN: AIR CAPABLE DD 963

FIGURE 5

ROCKET ASSISTED TAKEOFF

Provision for rocket assistance as a means of making a short takeoff even shorter or a catapult launch more effective was a normal feature of aircraft of the Royal Navy right up to the arrival of the big twin-jet aircraft. The Firefly, the Seahawk, even the stately Gannet, were all fitted out to accept Rocket Assisted Take-off Gear, RATOG.

Even today, RATOG is in service with the Buccaneers Mk.50 of the South African Air Force to assist them to get airborne from the high altitude airfields of their home country, and is currently being considered for restricted use in the Jaguar.

The rocket motor used in the Buccaneer is a Bristol Siddley BS 605, a descendent of the Bristol Siddley Gamma which powered the Black Knight rocket. It is fitted in the space normally occupied by the hold-back assembly in the Buccaneer of the Royal Navy, and, like the holdback, retracts into the fuselage after use. It delivers 8000 lb thrust for 30 seconds and is fuelled by a mixture of Kerosene from the aircraft fuel system and High Test Peroxide from a separate tank. HTP is not, however, a comfortable compound to have around, and indeed most of the expertise in liquid fuelled rocket motors in the United Kingdom has dispersed so this sort of motor is not worth persuing.

(A motor of similar output, however, is the Cuckoo, currently used in missile applications and powered by a solid propellant, and the question of how it would assist the launch performance of an aircraft of Sea Harrier proportions, if it were possible to graft it on, will be looked at later.)

A rocket motor achieves its thrust by burning its propellant and exhausting the resulting high pressure gases through a convergent-divergent nozzle. This runs in a choked condition, thus maintaining a constant mass flow, which combined with a constant exit velocity gives a steady consistent thrust. The condition at the throat being sonic however, means the motor is exceptionally noisy and its wake will be very erosive, both of which features militate against its suitability for use on board ship.

If such a motor were used for a skijump launch it would not be at all acceptable to have the rocket fizzle out while the aircraft was still accelerating along its ballistic flight path. Therefore rocket assistance must either cut out before the aircraft leaves the deck, or it must last until the aircraft is fully established in wing-borne flight so that sudden changes in trims and thrust do not add to the pilot's burden. Also, in the case of a rocket launch, it would be essential to have confirmation that the motor was working at full thrust before committing the aircraft to the launch. This requirement would add weight to the case for a holdback.

The assistance of a rocket motor in a flight-deck launch could be enlisted in three ways:

1. Rocket-assisted launch

2. Rocket-assisted launch and flight

3. Rocket-assisted flight

1. Rocket-assisted launch

For this the rockets must be working before the aircraft is released from the holdback, and must cut out before the aircraft separates from the deck. Flat deck launches of this sort are introduced in an R.A.E. paper on the subject of deck-run requirements for a Harrier aircraft (Ref.7) published in February 1975, before the idea of the skijump had become so well known.

The rocket installation considered in that paper consisted of four Scarabs, each one a solid fuel (cordite) rocket producing 3200 lb thrust for 6 seconds. For a combined thrust boost of 12800 lb the weight penalty was estimated to be a total of 800 lb.

The forecast performance improvement was as follows:

Deck run to launch aircraft of 22000 lb, given a headwind of 20 knots:

Dry = 570 ft

Rocket assisted = 350 ft

Alternatively, weight capable of being launched from 570ft

Dry = 22000 lb

Rocket assisted = 24100 lb

These estimates were made on the assumption that the time for the rocket to burn out would be matched exactly to the deck run. However, it was appreciated that under realistic conditions the rockets would have to be scheduled to extinguish before the aircraft left the deck, and so the apparent performance benefits would be reduced.

It was also considered that the takeoff run would be long enough for the pilot to start off with the jets pointing approximately aft for maximum acceleration and to have time to select the jets to their best downwards inclination as he passed the cue line on the flight deck. Given a shorter sharper ride he might not be able to do this, so the aircraft might have to set off with the jets already deflected.

The difference in forward thrust between having the jets deflected aft at 10°, (as has always been considered to be the case so far in this study), and having them preset to 50° is

$$19200(\text{Cos } 10^\circ - \text{Cos } 50^\circ) \text{ lb}$$

$$= \underline{6570 \text{ lb}}$$

This amount, which represents about one third of the initial acceleration force, must be at least equalled by the rocket thrust if a technique of starting with the jets already down is going to be employed.

Application of SCARAB Rocket to Skijump Launch

As demonstrated in the section on unaided skijump a 20,000 lb aircraft needing 75 ft/sec at the exit from a skijump of angle 20° requires a speed at the foot of:- 48 ft/sec

With the jets set aft and four Scarabs mounted, and making allowance for the extra 800 lb weight to accelerate, this required speed now comes down to:- 6 ft/sec

or very nearly a standing start.

However, fuller figures for a 20,000 lb and a 22000 lb aircraft using a 12800 lb booster pack weighing 800 lb are as shown below.

Total Weight	End Speed	Jet Position	Start Speed
20,800	85	Aft	40
		50°	55
22,000	110	Aft	85
		50°	90

These results do not offer much improvement on the unaided aircraft, which is rather disappointing considering the impression given by an extra thrust of 12,800 lb. The reason is not hard to find. A rocket system assisting in a deck launch needs to have time to make its effects felt. In attempting to shorten the length of a skijump launch by such a method, we are not giving it enough time to build up acceleration to a worthwhile value. All the deck launch rocket can offer is the equivalent of a catapult with an acceleration of well below one-half of g.

2. ROCKET-ASSISTED LAUNCH AND FLIGHT

The success of skijump and the ballistic launch lies in using acceleration in flight. Therefore it is logical that rocket-assistance, if used at all, must continue into the flight phase, and for reasons already mentioned, must endure beyond the beginning of the transition stage of flight.

In order to investigate what gains could follow the installation of a hypothetical rocket motor in an aircraft equivalent to the Harrier, the program SKIM devised for calculating end-speeds for the achievement of safe flyaway conditions, was amended to include the contribution of rocket assistance, and remustered as SKIR, Annex C.

The decrease in end speeds brought about by increases in the contribution of rocket assistance are depicted in Fig.6. It is noticeable that once the vertical components of rocket boost and deflected thrust combine to match the aircraft weight, a vertical or very very short takeoff becomes possible.

Application of the Cuckoo Rocket Motor to Rocket-Assisted Flight - (Boost = 8000 lb)

Using the RME Cuckoo rocket motor with 8000 lb thrust, were it possible to fit it to the Harrier, the launch speeds from a 20° ramp with nozzles deflected to 50° would be as follows:

Aircraft weight (lb)	Launch Speed (ft/sec)
22400	74
21400	60
20400	15

If the nozzles were advanced a further 5° to 55° the figures would be:-

Aircraft weight (lb)	Launch Speed (ft/sec)
22400	65
21400	32
20400	15

The speed at the foot of the skijump to give 22400 lb a final speed of 75 ft/sec is only 48 ft/sec (from Program SKID).

The distance to achieve this with the aircraft jets already set to 50° is 38 ft; making a total space requirement of:

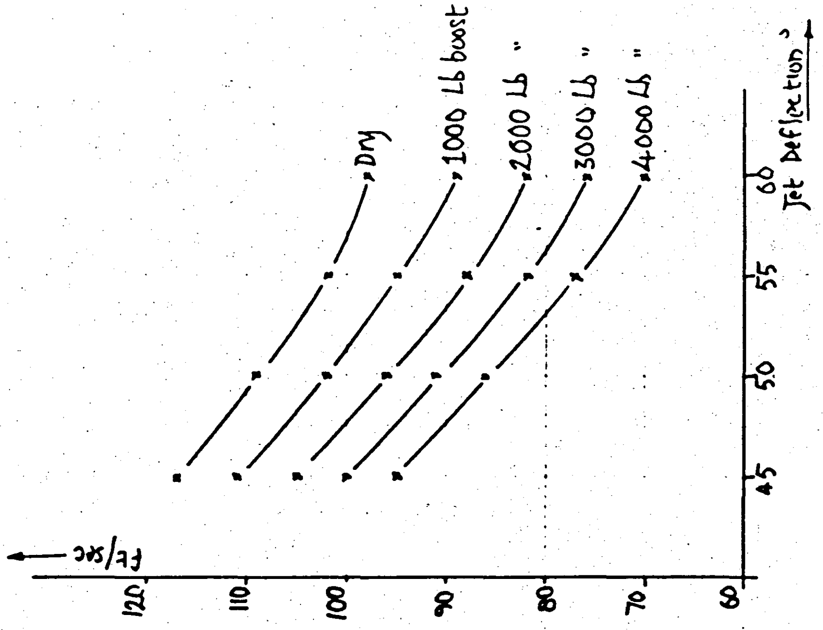
Curve = 180 x Sin 20° = 61.5 ft
Flat run = 38 ft
Length of aircraft = 50 ft
Lip extension = 11 ft
= 160 ft

which is 10 ft less than the distance required to launch a 20,000 lb aircraft, 2,000 lb lighter than the one considered, with no assistance.

The above figures are for the heaviest aircraft considered. An aircraft at 20,400 lb can get away from a standing start, and one 1000 lb heavier very nearly can.

ENDSPEED WITH ROCKET ASSISTANCE

Angle = 20°
Weight = 22,000 lb



ENDSPEEDS WITH ROCKET ASSISTANCE

Angle = 20°
Weight = 20,000 lb

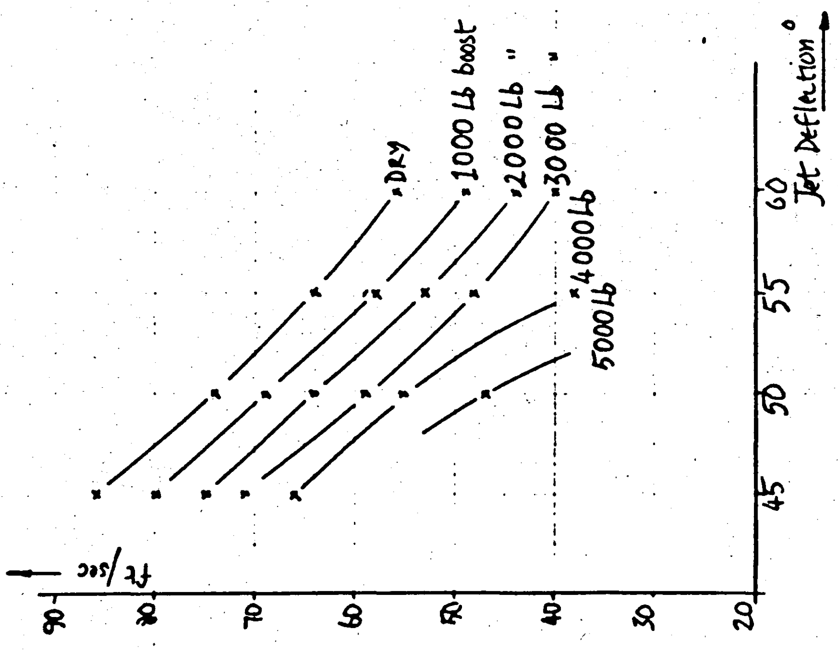


FIGURE 6. ENDSPEEDS WITH ROCKET ASSISTANCE

3. ROCKET ASSISTED FLIGHT

Rocket launch from the deck of a ship would be accompanied by an inacceptable amount of noise together with possible surface damage as well. Also its contribution to end speed is not really very great. Rocket assistance would be most useful in supporting the aircraft from the moment of leaving the edge of the skijump. If a rocket motor could be devised to direct its line of action in the same direction as the engine nozzles at this point, i.e. about 70° downwards, then the aircraft launch weight could be increased by an amount roughly equal to the rocket thrust less its own weight and that of its installation. It would have to be guaranteed to fire at precisely the right time, while, on the bright side, its noise and efflux would be directed at the sea and not at the ship.

Alternatively, rocket assistance could probably come into its own if it were applied to a VATOL aircraft in the particular context of launch from an overside platform. VATOL can be shown to have some advantages over HATOL as will be discussed in the final part of this paper, but it must be remembered that practical full-scale research in VATOL finished with the Ryan X-13 vertijet which has been a museum exhibit for over 20 years.

Rocket Motor Installation

The Harrier aircraft in its present form offers no suitable location for mounting an auxiliary rocket motor. The stores pylons could be considered as possible candidates on the grounds that they are served with electrical connections and are disposed around the aircraft with some symmetry, but the centreline pylon must be disqualified because the line of the rocket efflux runs right through the main undercarriage, and the inboard pylons, favourable because they would take a reaction line through the same plane as the aircraft centre of gravity, must be discounted too because they would lose their prime utility as weapon carriers.

The problem that adaptation of the current Harrier to rocket assistance would bring with it are, if not insurmountable, certainly uninviting. The aircraft would have to be shown to be capable of withstanding an upward force of two tons or more through either the engine bay in the case of a centreline mounting, or the wing roots for a pylon mounting, the pitching effects of the rocket reaction at extreme ends of the centre-of-gravity range would have to be within the authority of the aircraft's flying controls to overcome, while analysis of the disruptive effect that the rocket efflux would have on the interactions between the flow from the jet nozzles and the airstream entrained by them would probably call for a total rework of the measurements , calculations, and flight trials of years.

It must be concluded then that while rocket assistance undoubtedly has a lot to offer in terms of improving the extreme short takeoff performance of a vectored thrust aircraft so long as its accompanying noise and structural erosive effects are considered to be acceptable, it is most unlikely to be applied successfully to the existing Harrier. If its benefits are to be conferred on some form of Harrier successor then that aircraft will have to be designed with a RATOG capability specified from the start.

CATAPULT TAKEOFF

Just as the strike aircraft launched from a Fleet Carrier replaced the heavy calibre shell fired from a battleship as the supreme tactical weapon of the major Navies of the world, so did the big steam catapult supplant the gunhouse as the means by which it was despatched. Like the big gun, the long-stroke steam catapult was a formidable unit of machinery integral with the ship, and, again like the gun, if this formidable unit of machinery became unserviceable, the capability of the heavy ship to discharge its weapons was extinguished. Like the big gun too, the price of carrying the long-stroke catapult was high. The installation weighed something like 100 tons and it was all sited high above the waterline, detracting seriously from ship stability. The catapult in particular could impose a heavy drain on the ships own power supply - certainly in the later days of HMS 'Ark Royal' some very delicate tradeoffs had to be negotiated between the needs of the ship for live steam to keep her speed up on the one hand and the demands made by the accumulators of the catapult on the other. In launching a heavy aircraft the steam catapult expended something like 50×10^6 foot pounds of energy, and while without it the aircraft could not have been operated at all, the steam catapult's demise must have sent a sigh of relief whispering round the ranks of the ship constructor branch.

Now that the fixed-wing aircraft of the fleet can perform to a fair degree of adequacy without the assistance of a catapult or any other auxiliary adjunct to gaining the necessary end speeds for flight, the question must arise of is there any case whatever for reviving the catapult, and so reintroducing the problems and penalties that go hand-in-hand with it?

The answer has to be yes, with a plea of mitigating circumstances. The energy required to assist a VTOL launch is less than one tenth of that previously called for to launch a strike or fighter aircraft of the prior generation. A simpler catapult will do nicely.

It has been shown that while an aircraft of the Harrier type can takeoff vertically at an all-up weight of about 17000 lb, its payload can be increased by 3000 lb if it can be despatched from a 30° ramp at an end speed of only 60 ft/sec, and a further 40ft/sec will suffice to bring the launch weight up to 22,000 lb, representing an increase in payload of 5000 lb, nearly double the original.

The energies required for these launches are, respectively, 1.1×10^6 foot pounds and 3.4×10^6 foot pounds. The catapult to provide such launch energies as these will be in a different class altogether from the mighty steam catapult of the heavy fleet carrier. It can be smaller, lighter, and maybe independent of the ship for its energy supply. If it is in a single unit ship it will not need to be capable of repeated use as it will have plenty of time to recuperate after each shot, and it will not need a facility for rapid loading of the next aircraft.

Setting a target for energy of about 4×10^6 foot pounds, we will review the field of catapult machinery available or planned capable of meeting such a requirement.

The Lightweight Catapult : Historical

The lightweight catapult for launching aircraft from battleships and cruisers developed step-by-step along with the aircraft carrier. Although the Allies abandoned its use during the Second World War, going over entirely to the aircraft carrier, it is interesting to note (Ref.10) that the German Navy continued to rely on lightweight catapults for air reconnaisance and protection whenever their capital ships ventured beyond flying range of airfields. The Reference goes on to suggest that the Germans were well advanced in developing a system of using such catapults for rapid launching from the uncompleted aircraft carrier "Graf Zeppelin" and records the opinion based on study of the design that had she been brought into service she might well have matched the rate of launching aircraft displayed by the Allied aircraft carriers.

In the rapid loading and launching system as originally devised, the whole of the aircraft handling operation was to have been mechanised. Each aircraft would be loaded onto a catapult trolley as soon as it had landed on board, and it would remain on this trolley while being manoeuvred along rails on the lift, within the hangar, around the flight deck, and finally, back onto the catapult.

All the German catapults were powered by compressed air. A jack from the main catapult cylinder actuated a sliding girder tethered to the launch trolley by way of a wire rope following a 3-1 reeving system, that is, the trolley stroke measured three times that of the sliding girder which therefore needed only a short travel. Features of special interest included a pneumatically-operated holdback. The rapid - loading function made use of interchangeable trolleys, each of which could be brought up ready loaded with an aircraft mounted upon it, and automatically attached to the wire rope system. Also incorporated was a method of discarding the trolley automatically after the aircraft had been launched.

The sliding-girder type of catapult had one main disadvantage, namely the weight of its moving parts which hade to be accelerated and then retarded after every launch cycle. The equivalent weight of these parts when considered as acting on the trolley added up to about twice the weight of the aircraft, which was typically 7000 - 11000 lb. This drawback, together with the realisation that the power cylinder exhausted at a fairly high pressure at the end of its stroke, meant that efficiency would not have been at all high.

Typical performance figures were as follows:

Rapid-loading catapult for 'Graf Zeppelin' and 'Deutschland'

Aircraft Maximum Weight = 11000 lb
Takeoff Speed = 72.3 kts
Maximum Acceleration = 3.87 g
Mean Acceleration = 3.27 g
HP Air Bottle Pressure = 1750 lb/in^2

The energy transmitted to the aircraft as a result of such a launch

$$= \tfrac{1}{2} \times 11{,}000 \times (72.3 \times 1.66)^2/32.2 \text{ foot pounds}$$

$$= \underline{2.5 \times 10^6 \text{ foot pounds}}$$

Comparison with the target energy requirement of 4 x 10^6 foot points shows that the pneumatic catapult is clearly worth considering.

The Lightweight Catapult - Present and Projected

Although the steam catapult is predominant in its field in ships at sea, steam propulsion does not hold the monopoly of all launch aids available today. Other methods are still in use or under development, and these include winch launches, inertia accelerators and the reborn pneumatic catapult itself.

Preliminary researches into the market reveal the existence of four types of lightweight catapult systems, either in use or on paper, either of which might be suitable for use in a small ship. The types considered are:-

a. The CE 1-3 catapult (Ref.11)

b. The SERD catapult (Refs.11 and 12)

c. The so called "low energy pneumatic launcher"(Ref.11)

d. A controlled burning Cordite catapult (Ref.14)

a. The CE 1-3 Catapult

This system uses an endless tow cable pulled by a capstan driven by a free turbine gas generator. In its original form it has been in use by the US Marine Corps as a semi-portable shore-borne launch aid for over twelve years. It provides a launch speed of 120 knots at aircraft weights approaching 25000 lb. Being in effect motor-driven its acceleration is limited to 2.5 g so it requires a relatively long stroke. This can be reduced to as little as 150 ft which while suitable for an aircraft carrier or "Harrier Carrier" type is still too long for small ship application. It is independent of ships power and considerably lighter than a steam catapult, and is worth bearing in mind for flat-top application. The layout is at Fig.7.

b. The SERD Catapult

The Stored Energy Rotary Drive catapult has its origins in the flywheel-and-drum catapults described in the early R.A.E.Technical Notes of the late 1930s and early 1940s. Essentially an internal-combustion engine was used to spin up a mighty flywheel to a high rate of revolutions per minute. When stabilised this flywheel was clutched onto the drive of a winchdrum which snatched in a cable to which was attached the connection to the aircraft to be launched. Early wartime studies included a catapult capable of launching a Fairey Fulmar to a speed of 60 knots over a distance of 60 ft, and a more ambitious scheme devised with the intention of launching a Halifax bomber at a daunting all-up weight of 70,000 lb. American developments of the idea, appearing in brochure form in the late 1960s included a flush-deck installation driven by a self-contained gas turbine and designed to impart an end speed of 120 knots to an aircraft weighing 120,000 lb, using most of the axial flight deck of a heavy aircraft carrier as its acceleration lane.

SERD development is currently proceeding at the US Naval Air Engineering Centre, Lakehurst, New Jersey and is mainly directed towards producing a replacement or competitor for the current steam catapult. All the parameters now are massive. Wire rope has been superseded by elastomeric tape with a breaking strength of 880,000 lb, the prime motor is rated at 10,000 Horsepower, the flywheel is of 5'8" diameter and weighs over 13 tons. While developments on this scale place the particular SERD catapult referenced right out of the class required for a VTOL aircraft it is hinted that a small-scale SERD launcher may be under consideration (Ref. 12), while a diagram of such a device, taken from Ref. 11 is reproduced as Fig.8.

c. The Low Energy V-STOL Launcher

The low energy V-STOL launcher, (Ref. 11), brings us back to the pneumatic catapult off the "Graf Zeppelin". The schematic layout of a Deutsche Werke training catapult is shown at Fig.9 (upper) and is not at all dissimilar to the layout of a pneumatic launcher shown in Fig.9 (lower).

The low energy launcher is wholly new in that it would be applicable solely to VSTOL aircraft, and is designed for end speeds of up to 60 knots. For a VSTOL aircraft in the Harrier/AV-8A class it transmits an energy of 4×10^6 foot pounds, which, for thepurposes of this paper, is right on target. By providing a tow force of up to 4 g, the power stroke is short, about one aircraft length, 30-45 feet. The launcher is built as a single unit with a cross-sectional area of less than 5 ft^2 and a weight of less than 10,000 lb. Two types are considered, one transmitting its thrust by means of a directly-driven shuttle, the other using a cross-head and cable connection.

Both are illustrated in Fig.10,shown as they would be if mounted in the deck of a frigate (Illustrations taken from Ref. 11).

Being both short and compact, the low energy launcher can be mounted in a tilted attitude, and so is unique among the catapults under discussion in that it lends itself directly to being used for an upwards ballistic launch.

A diagram of the low energy launcher set up for a 30° inclined launch is reproduced in Fig.11,also taken from Ref. 11 .

Sample Calculation - Air Catapult

1. Calculation of Piston Pressure

Aircraft weight = 21,000 lb, Angle = 15°, Stroke = 45ft

From Fig.1, endspeed = 79 ft/sec

'g' required = 2.15

If moving parts of catapult weigh 1000 lb,

Total force = 22,000 x (2.15 + Sin 15°)

= 53,000 lb

Contribution from aircraft = 17,000 Cos 50°

= 10,927 lb

Nett force at piston = 42,070 lb

If piston diameter = 10"

Pressure at piston = 535 psi

2. Calculation of accumulator pressure

Let Accumulator pressure = P_1

Piston pressure = P_2

Accumulator volume = V_1

Catapult volume = V_2

Then

$$P_1 V_1^{\gamma} = P_2 (V_1 + V_2)^{\gamma}$$

$$P_1 = P_2 \left[\frac{V_1 + V_2}{V_1}\right]^{\gamma}$$

e.g. for a compression ratio of 2.5,

$$P_1 = 535 \times (2.5)^{1.4} \text{psi}$$

$$= 1930 \text{ psi}$$

(cf Air bottle pressure for Graf Zeppelin catapult of 1750 psi).

d. The Cordite Catapult

A cordite catapult would consist simply of a breech plus a ram tube carrying a piston capable of transmitting its motion to the shuttle drawing the aircraft. Ignition of the cordite charge in the breech would result in a buildup of gas pressure, typically up to about 5000 psi in about 1½ seconds. This gas exhausts into the ram tube through a nozzle which would be designed to run in a choked condition, ensuring a consistent mass flow and so maintaining a consistent pressure behind the piston. The action is quite fast and therefore it is desirable to introduce gearing between the piston and the shuttle. This would be done by mounting a pulley as the crosshead of the piston rod, and reeving a rope around it, anchored at one end and connected to the shuttle at the other, thus achieving a 1:2 velocity ratio. A further advantage of this arrangement is that most of the moving parts of the catapult are travelling at only half the speed of the aircraft, and therefore it will be easier to bring them to a standstill after each launch cycle (Fig.12).

The rate at which gas is generated is a function of breech and charge design. The charge takes up about half the volume of the breech initially leaving space to act as an initial reservoir,and is configured so that the surface area burning increases with the burn time. In this sort of application the charge would consist of one or more hollow tubes of propellant, inhibited on the outside and burning from the inside outwards. The propellant itself, (CSC½K is suggested by the Rocket Motor Executive), is a double-based charge (i.e. comprising nitroglycerine and nitrocellulose together) of what is classed as a low explosive, which would have a long shelf life and would need to be kept in magazine conditions. The whole machine would be operated like a gun but with a charge that burns rather than detonates.

Sample calculation - Cordite Catapult

For the same conditions as the previous catapult considered the moving parts of the catapult are accelerated twice as fast as the aircraft

$$\text{Force on aircraft} = 21000 \times (2.15 + \sin 15^\circ) - 17000 \cos 50^\circ$$

$$= \underline{39{,}658 \text{ lb}}$$

$$\text{Force on piston} = 2 \times 39658 + 1000(2.15 + \sin 15^\circ)$$

$$= \underline{81725 \text{ lb}}$$

$$\text{Piston pressure} = \underline{1040 \text{ psi}}$$

The charge to produce this pressure and sustain it over the whole stroke would probably not weigh more than 20 lb. (A more precise estimate could be obtained from the

Rocket Motor Executive, MOD (PE)). RME can demonstrate too that a single charge size will give a satisfactory launch to a wide range of aircraft weights.

AIRCRAFT MODIFICATION FOR ASSISTED TAKEOFF

At present neither the Harrier nor the AV-8A is stressed or equipped for catapult takeoff, and this shortcoming could easily be the deciding factor in rendering all discussions on launching by catapult purely academic. A study has been undertaken (Ref.13) to determine the modifications necessary to make an AV-8A suitable for assisted launch and it has been estimated by McDonnell-Douglas that the additional weight penalty for a launch at 3g would be something of the order of 150 lb to 390 lb depending on whether a bridle or a tow-bar is used. (These figures are not endorsed by British Aerospace who do not view the project with anything like positive enthusiasm).

A design problem in catapult launching arises from the current Harrier having a tandem undercarriage, which means that with a conventional shuttle arrangement in use the main wheels would have to override it at the end of each stroke. (This is why the version of the Hawker P1154 intended for the Royal Navy would have had a conventionally disposed tricycle undercarriage). One proposed solution to this problem would be for the towing attachment to consist of a channel-section cradle hooking on to the aircraft with a pair of trunnions at a point ahead of the nose wheel as is suggested by Fig.11.

No further progress has been made following the McDonnel-Douglas design study. It is possible that if the US Government decides to order the AV-8B for the US Navy then interest in adapting the aircraft for catapult launching might be rekindled very rapidly.

COMPARISONS

Four methods of getting airborne have been looked at, two unassisted, and two using auxiliary thrust. Their properties can be summed up as follows:-

1. Vertical Takeoff

As with any aircraft, vectored thrust or not, all attempts at improving its flying qualities at the takeoff end of its performance spectrum will have to be made at the expense of some degradation at the high speed end. Unless it is the operator's firm intention to use VTO as the predominant mode of getting airborne, some at least of the aids to improvement will have to be rejected. Those which by reducing adverse recirculation and suck down effects can improve behaviour at landing as well as on takeoff should of course be progressed in any case.

The flight deck grating has been considered. Since it was first schemed up, lift improvement devices have reached a level where they can offer a greater increase in takeoff weight than the grating was ever expected to. Furthermore this increase is available in landing weight also, which the grating, by virtue of its limited size, cannot offer.

The flight deck grid or grating then need be considered no further.

2. Skijump

The skijump can be shown in theory to have the potential to launch aircraft right up to the maximum all-up weight allowable from a flat surface. With the current aircraft this potential is limited in practice by the aircraft's undercarriage. Firstly, the rate at which the is loaded by the centripetal force caused by the aircraft running round the skijump radius is far less than its damping was intended to withstand, and secondly, a combination of speed and skijump radius is bound to be reached at which the suspension bottoms altogether.

This problem can be overcome, or at least postponed as long as possible, by re-engineering either the skijump or the suspension of the aircraft or both of them together. One solution is to have a skijump of bigger radius. This would mean that the area of flat deck available for other activities such as helicopter operations or deck parking would have to be less. For the undercarriage to be redesigned to the limit the user service would have to justify the exercise by convincing itself of its intention to operate at the higher launch weights made possible.

As far as aircraft of the next generation are concerned, their undercarriages would have to be designed for operation off the skijump from the beginning. This might not be too demanding a problem however. If aircraft of the next generations have a higher performance than those of the current one, (and this is usually the case), then as it has been shown that increases in thrust are repaid very handsomely by reduction in the required end speed for launch then these speeds might not necessarily be higher than at present; indeed they are likely to be lower.

3. Rocket Assistance

As has been shown, applying rocket assistance to flight from a skijump leads to results that are most encouraging in theory. The practical implications of rocket assistance are such, unfortunately, as to cancel this encouragement right out. The costs of rocket assistance in terms of noise, deck erosion, loss of payload space, the problem of reworking the aircraft to make it capable of accepting a thrust line through a point right in the middle of the existing engine installation, and the difficulty of keeping the aircraft controllable equally well in partial jet-borne flight with the rocket burning as in having flight with it off, all go together to make RATOG a complete non-starter as far as the current aircraft is concerned.

An aircraft of a succeeding generation could benefit from RATOG only if it were designed to take-off in a vertical attitude. Otherwise, any aircraft taking off in a horizontal attitude would be better served if it were fitted with a lift engine. For equivalent thrust this would weigh no more than a rocket motor, nor would it take up any more space. Unlike the rocket motor however, it could earn its keep not just on takeoff but on landing also. But such an aircraft would now be suitable for vertical takeoff only. A single lift engine would not be capable of being installed in such a way as to have its thrust line extending through the pitch centre. The only way round this would be to balance it with another lift engine.

Thus the original aircraft which had started life with the pleasing simplicity of a single engine installation would finish up with the layout of a YAK-36 and be limited to vertical takeoff only, or would have the layout of the VAK-191-B and be capable of skijump launches but only at a very shallow angle and after a lot of difficulties had been overcome.

It appears evident then that there is no straightforward way by which a vectored-thrust aircraft could have its takeoff performance improved with additional thrust from an auxiliary engine, be it rocket or jet, without losing its identity altogether.

4. Catapult Launching

We have seen that a vectored thrust aircraft could achieve the same ballistic launch from a catapult as from a skijump, and that with the catapult acceleration being about four times that along the skijump, the length of the catapult track would be about a quarter of the skijump run for the same end speed. We have seen too that the nature of a suitable catapult is such that it could be developed without the need to cross any unknown frontiers of engineering. The propellant could be either compressed air or cordite, and for a given performance requirement to be met there would be no significant difference in size or shape of the catapult whichever one was chosen.

If a choice had to be made between the two it would have to be based on criteria extra to performance and size.

The parts of the catapult interfacing with the aircraft would be similar in size, complexity, and cost whatever the type. The workings below decks, however, at the end where the power comes from, would be very different. A pneumatic catapult would need air compressors, high pressure storage vessels, a regulation and control system, plus all the plumbing that goes with them, and all of them would need maintenance. A cordite catapult on the other hand would need nothing more complicated than a breech mechanism, and that would require little specialist attention other than periodic renewal of its nozzle orifice.

On this simple assessment the cordite catapult certainly has the advantage over its competitor. Its adoption would mean that one of the features of the rocket motor that made it so attractive, viz its use of the energy stored in a solid package of fuel as a source of extra thrust, would still be retained, and in a most efficient way.

SELECTION OF A SYSTEM FOR A SHIP

With the use of rocket assistance having been rejected on grounds of impracticability, there still remain three methods of getting airborne to be considered - unassisted Vertical Takeoff, skijump takeoff and takeoff from an inclined catapult.

If the merits of these three are to be compared and contrasted in a fair manner it is not sufficient to evaluate them just on their absolute qualities alone. Instead they should be considered in conjunction with the ship in which they are likely to be used.

Vertical Takeoff

No matter how big a payload an aircraft can carry in a Vertical Takeoff, it will always be able to carry more if it gets airborne in forward flight. Vertical takeoff will continue to be the launch method offering the smallest payload, and if in spite of this it is to be used at all there will have to be a sound reason for it.

This reason will be that there will be no space available in the ship for any other form of takeoff to be practiced. This implies operation from a single unit ship on the premise that if there is room for a skijump or catapult then there will be room too for further aircraft to be embarked.

For a single aircraft, utilisation will be low, only about four or five sorties a day at the most. (See Part 4 'Availability').

This would be the utilisation of the catapult if there were one. Could such a low utilisation justify the cost of procuring and installing such a large equipment in a ship where competition for any space at all would be so fierce? The answer could only be yes if the tasking of the ship were critically dependent upon the ability of its aircraft to carry a payload about 4000-5000 lb higher than that which it could carry unaided, an aircraft moreover which considerations of support would limit to brief embarkation periods only, and which comprised only part of its weapon system anyway. The unlikelihood of this bein g so, plus the cost of installing catapults at a rate of one per aircraft, means the answer must surely be no.

Where this apparently circular logic leads to is the establishment of the principle that an aircraft operating from a single-unit ship will have to make do with unaided VTO for getting off the deck, and the limitation of its relatively low (but nevertheless impressive) payload will have to be accepted. If this limitation is seen to impose a severe operational restriction on the aircraft, then this will serve as an incentive to progress methods of making unaided VTO more efficient. In a single-unit ship the jet VTO aircraft would be a direct competitor with the helicopter and other VTO hybrids.

The Skijump compared with the Catapult

A flight deck some 250 ft long ending with a 15° ski-jump, and a catapult with a 45 ft stroke inclined at the same angle could both launch an aircraft at the same all-up weight, and both these methods of launch could be developed to the point at which an aircraft at its maximum airfield takeoff weight could be handled. The question is one of how to choose between the two systems.

At first sight the catapult offers the inducement of compactness. This leads to the suggestion that it could be slotted neatly into a small ship, so arming it with a full fixed-wing warplane capability. This unfortunately is not quite a full statement of the case. There are arguments countering it on both engineering and economical grounds.

First the engineering points. While the catapult stroke itself is short, the installation would have to be longer. The front would have to be extended by about 5 ft to accommodate the system for arresting the piston at the end of its stroke, while at the back there would need to be space to manoeuvre the aircraft up to its point of launch. On top of all that the whole artefact has to be able to tilt, and for the catapult track to be flush with the deck the trough below the deck which accommodates the catapult workings would have to be extended back to make room for the overhang of the aircraft (See Fig.11). All this means weight and space, and the question of where the jet blast goes to has still to be considered too.

The length of the catapult and its approach area is now nearer to 90 ft than to 45 ft, and so it would be too big to be orientated in any direction other than diagonally or fore-and-aft. Indeed unless it were to be so powerful that the assistance offered by the windspeed over the deck could be disdained, the more nearly fore-and-aft it would point the better. Ideally it should be right forward ahead of the bridge, thus monopolising areas more profitably used for siting less extravagant weapon mountings; its second choice would be aft, and pointing along the side of the ship at an angle.

The economical drawbacks have already been suggested. The equipment would need to be justified on a basis of cost-per-launch for the extra payload gained, and this would be difficult against the alternatives, which would include the expedients of placing the ship nearer to its target or extending the range of the air-launched weapon, as well as installing a simple skijump. (The case for developing an inclined catapult for use ashore might be a little firmer, because one equipment could service any number of aircraft, and space ashore is not at a premium).

Given then a 90 ft length of deck angled from the after end of the ship, the choice lies between the following: either to design, develop, fund, prove and establish a tilting catapult able to cope with not just aircraft of this generation but the next one as well, and then to purchase and install it in enough air capable ships to make it worthwhile, or to extend this deck by another 160 ft or thereabouts, so creating a flying-off deck with an equivalent operational capability but no development costs and no moving parts.

(A third choice, that of building a horizontal catapult firing its aircraft into a skijump is mentioned only because it has been suggested elsewhere. It manages to combine all the disadvantages of both systems into an installation the size of the largest one).

Clearly the skijump must emerge as the best buy. It is already under development, it is fitted to two ships of the RN fleet with another two to follow, and it can become more efficient for a given structural length as engine thrust increases, as it surely must.

CONCLUSIONS

In a comparison of Vertical Takeoff, launch from an inclined catapult and flight from a skijump it has been shown that catapult launching has to be rejected in a small ship scenario on grounds of space and utilisation, while on a ship large enough to have space available for launch assist devices it takes second place to a skijump installation on grounds of efficiency. Rocket assistance, while attractive in theory is impracticable to realise, and is discounted altogether.

The following conclusions emerge:-

1. Vectored thrust aircraft operating from single unit ships will get airborne with unaided Vertical Takeoff.
2. The most efficient launch assist installation on offer for larger ships is the skijump. A skijump of about 250ft can match the launch benefits conferred by either Rocket or Catapult assistance.
3. The increased thrust likely in the next generation of aircraft will lead to better performance both in VTO and in skijump launching, especially the latter.

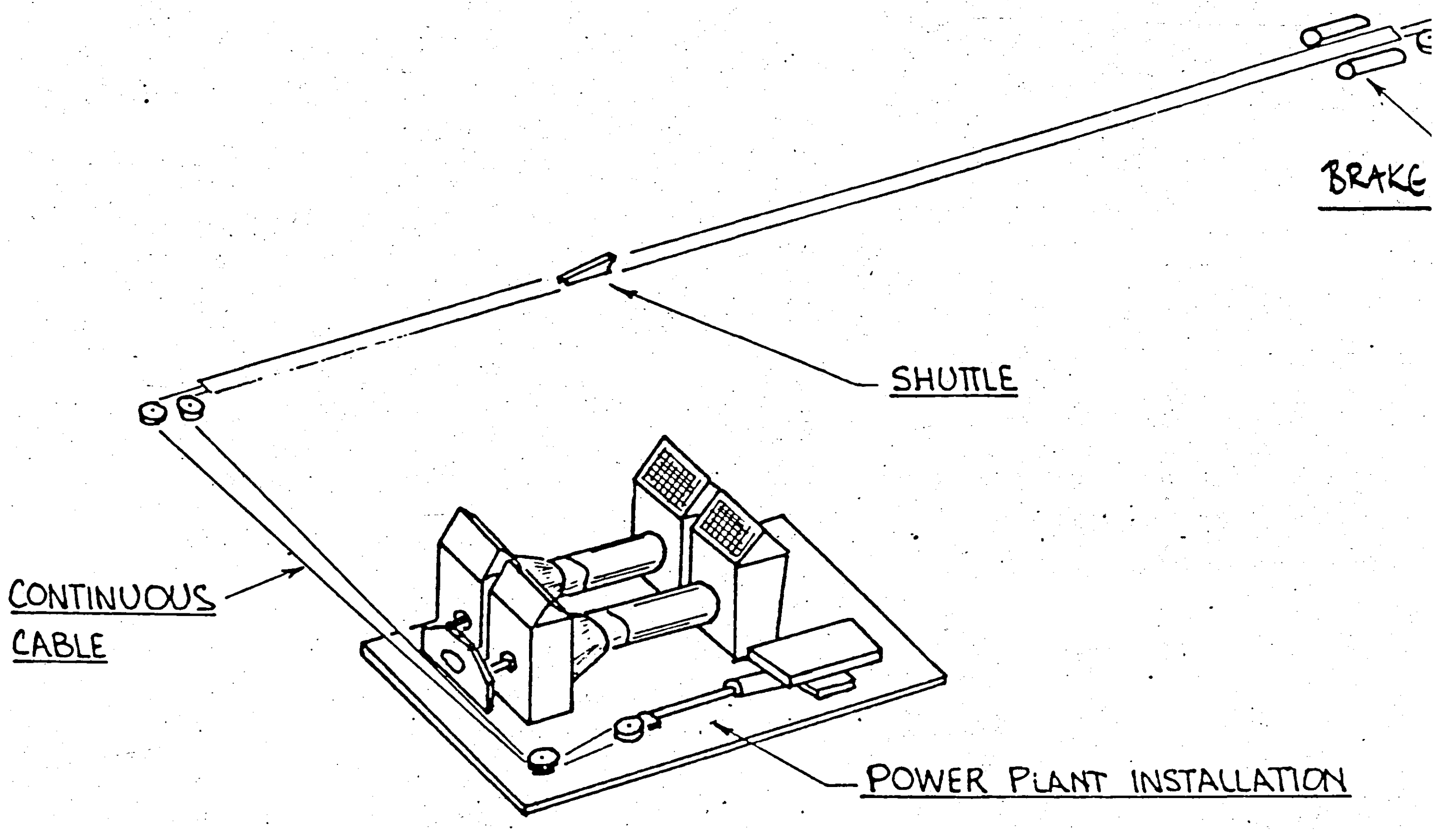


FIGURE 7. CEI CATAPULT - MODIFIED FOR SHIPBOARD V-STOL AIRCRAFT USE.

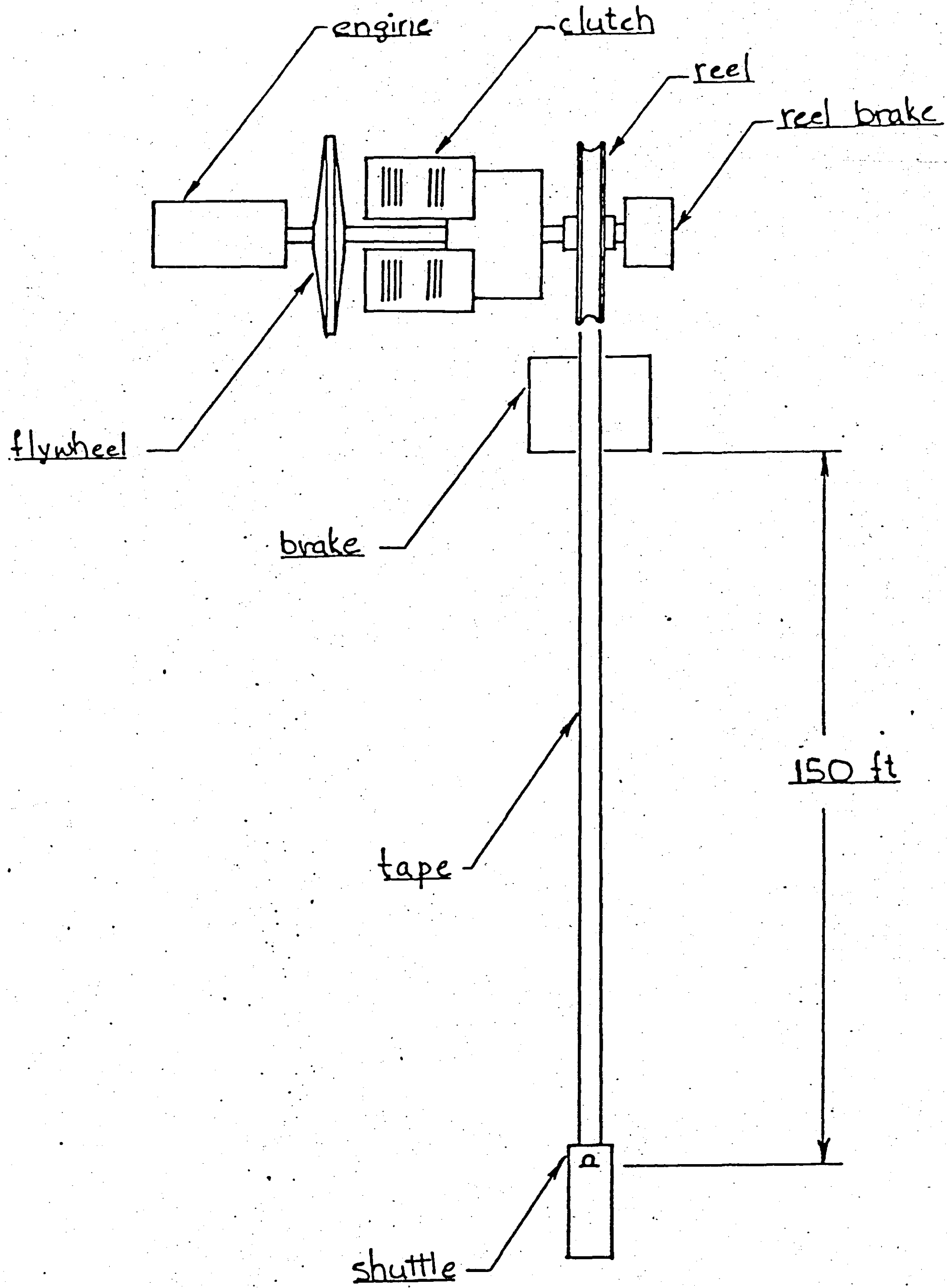
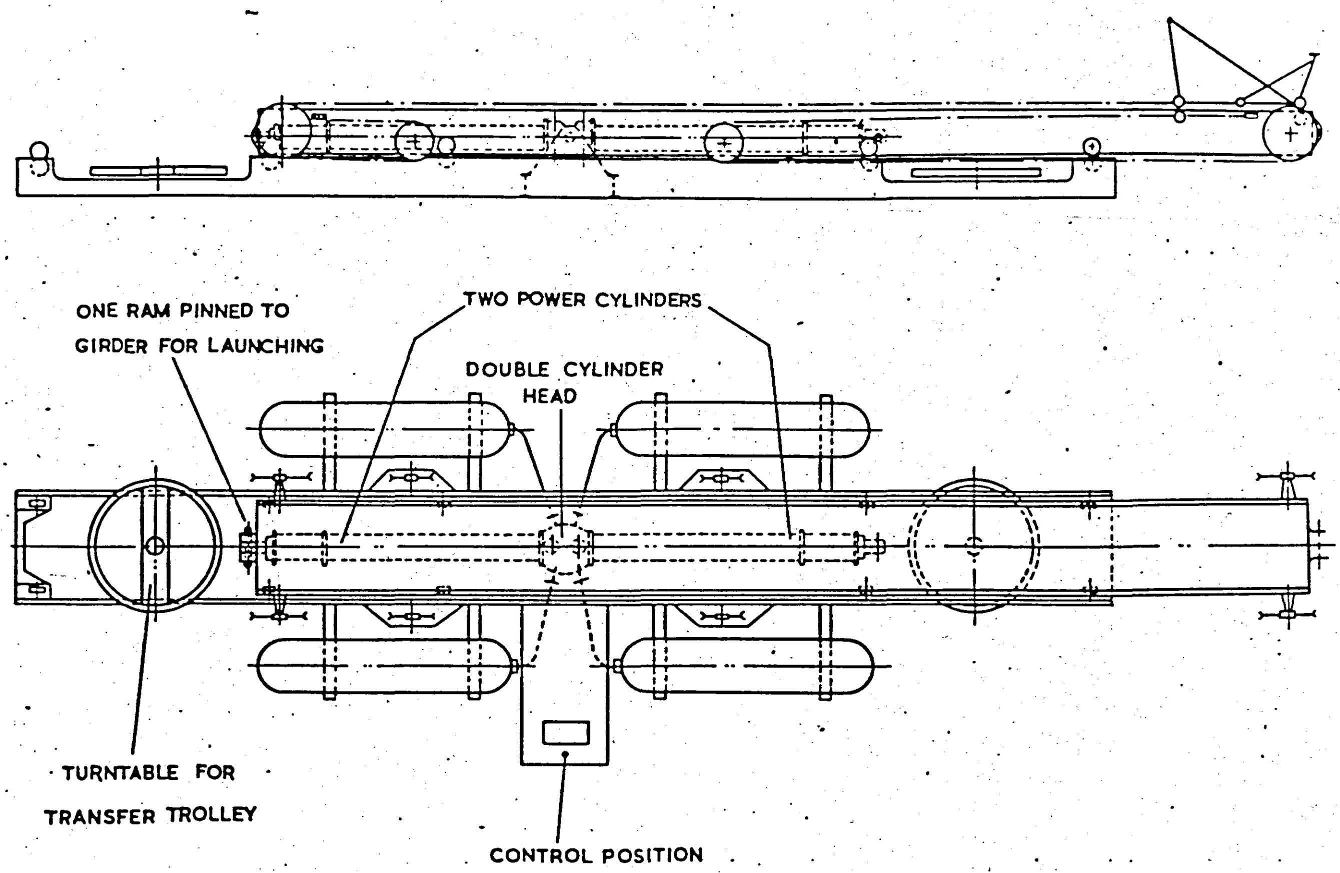


FIGURE 8. SMALL SCALE SERD CATAPULT.



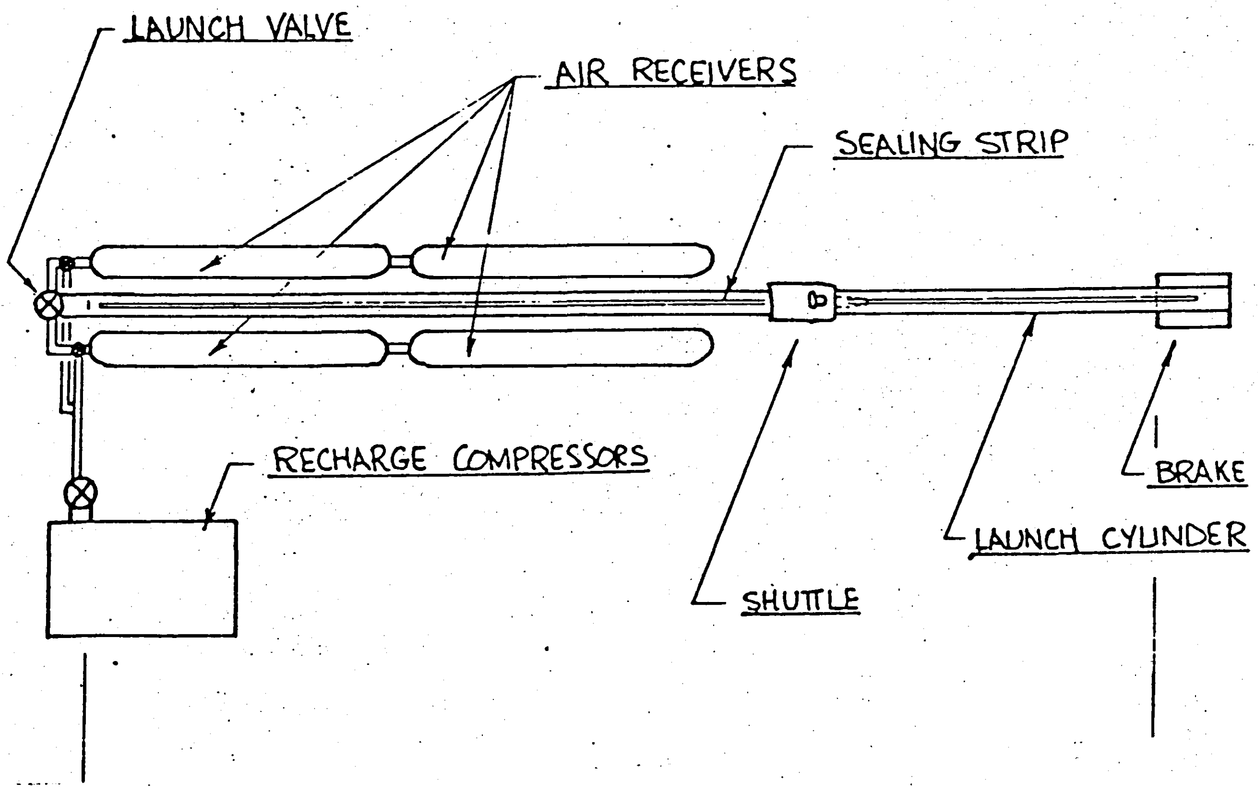


FIGURE 9. ABOVE : DEUTSCHE WERKE CATAPULT
BELOW : PNEUMATIC LAUNCHER FOR V-STOL AIRCRAFT

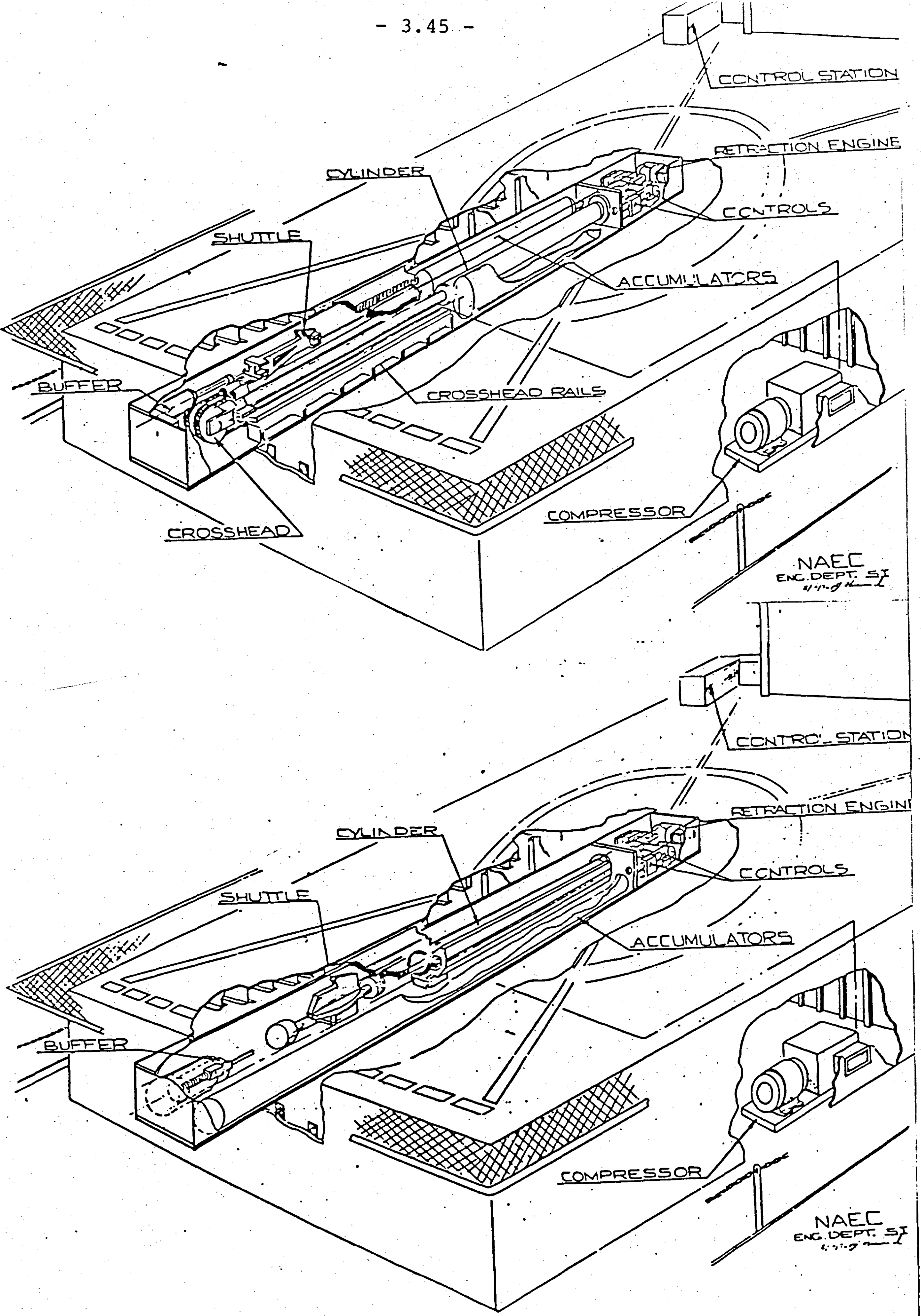


FIGURE 10. LOW ENERGY V-STOL LAUNCHER

ABOVE : PISTON/SHEAR

BELOW : STRIP SEAL

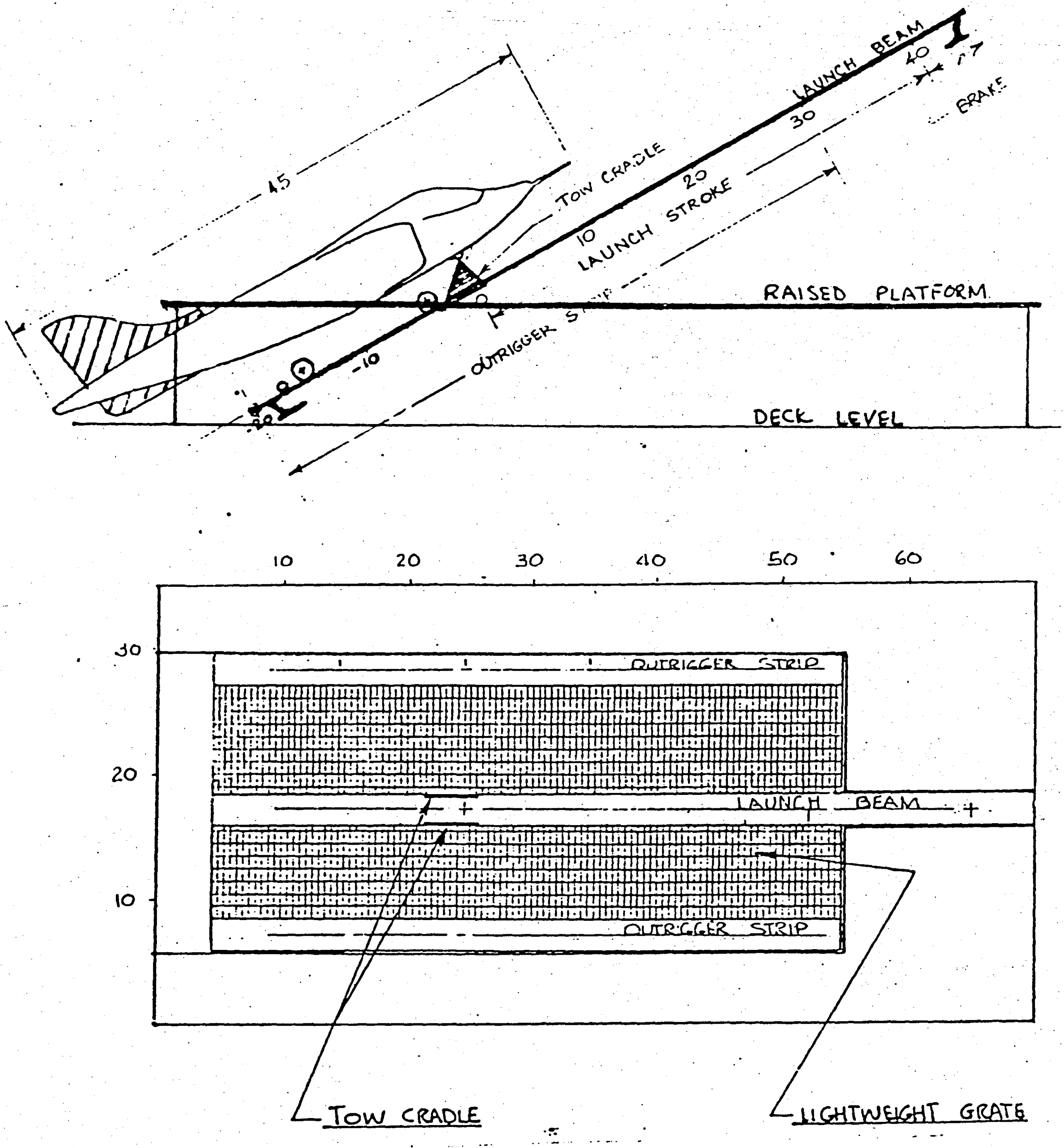


FIGURE 11. AV-8B MOUNTED ON LOW ENERGY INCLINED LAUNCHER

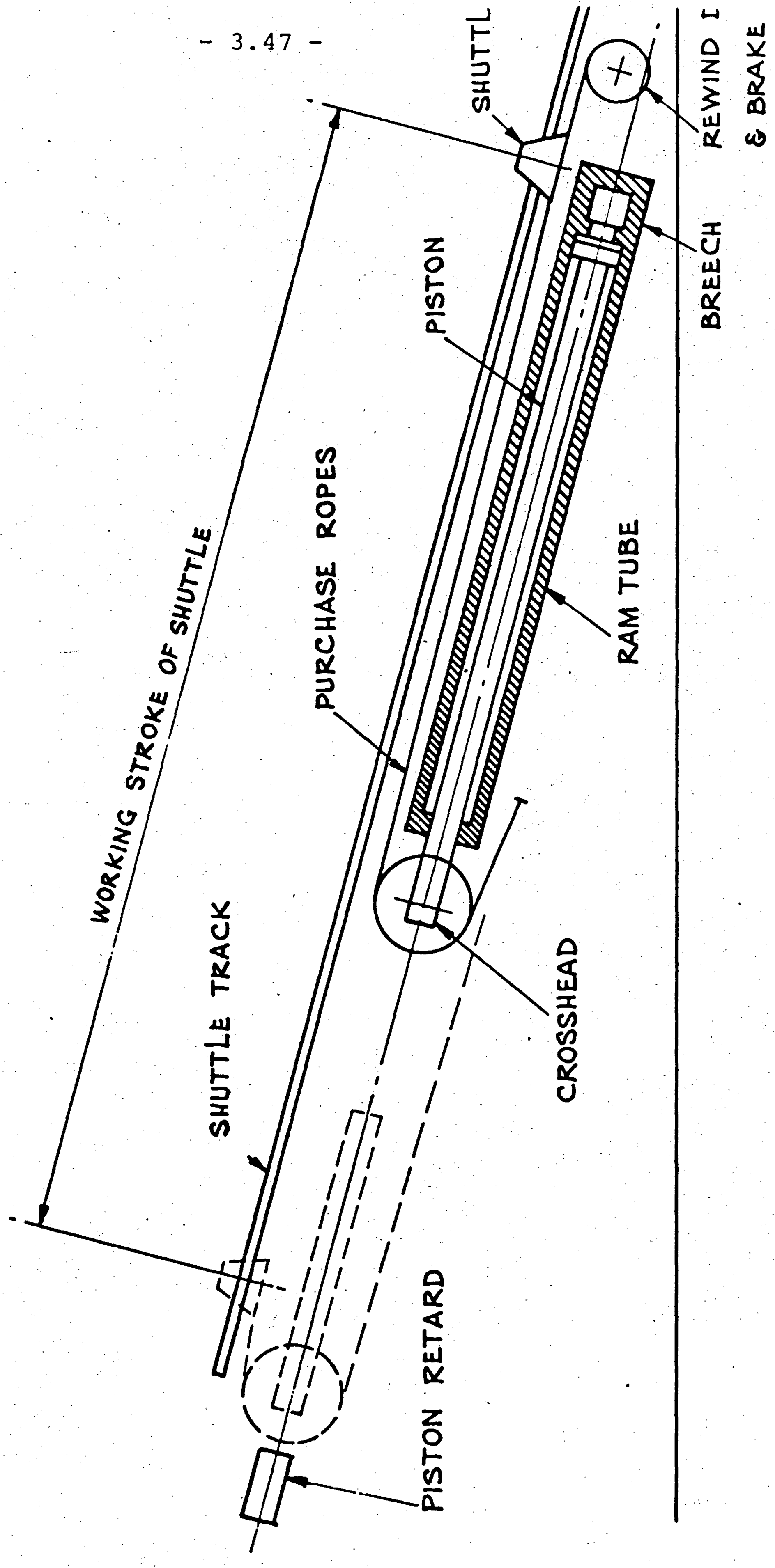


FIGURE 12. CORDITE CATAPULT

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ANNEX A TO PART 3

ACCELERATION DURING TAKEOFF

From Ref.6, for the Harrier:

$$C_D = 0.13 + 0.1\ C_L^2$$

and Intake Drag = 24.2 lb/knot = 14.5 lb/ft/sec

From the Taylor thesis it is known that the Harrier will fly at a weight of 22000 lb, speed of 200 ft/sec and thrust of 19200 lb deflected down to 60°.

In this condition, the wing lift contribution is

= <u>5372 lb</u>

Hence, $\frac{1}{2}\rho S C_L (200)^2 = 5372$

so $\frac{1}{2}\rho S C_L = 0.1343$

At 12° ADD $C_L = 0.95$, from Ref.6 Fig.1

Thus $\frac{1}{2}\rho S = \underline{0.1413}$

On rolling, taking the static incidence as being 7°,

$$\begin{aligned} C_L &= 0.72 \text{ (Ref.6, Fig.1)} \\ \therefore\quad C_D &= 0.13 + 0.1 \times (0.72)^2 \\ &= 0.182 \\ \therefore\quad \text{Drag} &= V^2 \times 0.1413 \times 0.182 \\ &= V^2 \times 0.0256 \end{aligned}$$

At 100ft/sec

$$\begin{aligned} \text{Drag} &= 0.0256 \times 100^2 + 14.5 \times 100 \text{ lb} \\ &= 256 + 1450 \text{ lb} \\ (\text{Lift} &= 0.1413 \times 0.72 \times 100^2 \\ &= 1017 \text{ lb }) \end{aligned}$$

So (Profile Drag + Induced Drag) = 1.3% of Thrust and only Momentum Drag remains to be considered.

With a jet deflection of 10° and an assumed coefficient of friction for a steel deck of 0.025:-

$$\frac{W\dot{V}}{g} = \text{Thrust} \times \cos 10^\circ - 14.5V - 0.025\ (\text{Weight} - \text{Thrust} \times \sin 10^\circ)$$

Thrust

It is understood from RAE Bedford that the nett thrust developed by a Harrier engine when accelerating the aircraft on the ground is approximately 17000 lb, the difference between that figure and the net value in flight of 19200 lb being due to recirculation and ground interference effects. So for ground accelerations, 17000 lb is the figure which will be used.

With an aircraft weight of 22000 lb,

$$\frac{W\dot{V}}{g} = 17000 \cos 10^\circ - 14.5V - 0.025\ (22000 - 17000 \sin 10^\circ)$$

Whence $\underline{\dot{V} = 23.8 - 0.021V}$

The diminutions of $\dot{V}$due to V being even as high as 100 is less than 10% and this will be taken as justification for assuming acceleration to be constant under the terms of the Paper by Krenkel and Seitzman (Ref.8). Where necessary the value of $\dot{V}$ will be reduced by an amount equal to the constant (0.021) multiplied by the average V.

ANNEX B TO PART 3

ACCELERATION AROUND A CURVED SKIJUMP OF CONSTANT RADIUS

Consider the conditions of an aircraft partway around a curve in the vertical axis of Radius R and Exit Angle A degrees.

At some position α around the curve, the net accelerating force in the direction of motion is:

Thrust x Cosine (Jet deflection) - Weight x Sine α

For a thrust of 17000 lb and jet deflection of 10^{o};

$$\text{Acceleration} = \frac{g}{W}(16741 - W \text{ Sine } \alpha) \qquad (1)$$

For small angles it is acceptable to assume approximate linearity between α and Sin α. Treating the conditions as being equivalent to a uniform rate of change, let:-

V_R be speed at entry to curve

V_L be speed at exit, e.g. launch speed

a = acceleration

Then

$$V_L = \sqrt{V_R^2 + 2aRA. \pi/180} \qquad (2)$$

Friction force opposing acceleration:

$$= \mu\frac{WV}{Rg} + \mu(W - 17000 \text{ Sin } 10^{o}) \text{ Cos } \alpha$$

$$= \mu W(\frac{V^2}{Rg} + \cos \alpha(1 - \frac{2952}{W}))$$

Taking μ as 0.025:

$$a = \frac{g}{W}(16741 - W \sin\alpha - \mu W(\frac{V^2}{Rg} + \cos \alpha(1 - \frac{2952}{W})) \qquad (3)$$

The stages of calculation of V_L are now as follows:-

(i) Using equation (1) calculate average accelerations at a point halfway around the curve.

(ii) Use this value to calculate V_L from equation (2)

(iii) Use an average $V = \frac{1}{2}(V_L + V_R)$ in equation (3) to calculate a corrected acceleration

(iv) Feed this into equation (2) to yield a corrected V_L.

Two iterations suffice to stabilise this value.

Example

Take values as follows:-

$W = 24000$, $A = 15^{\circ}$, $R = 400$, $V_R = 77.3$

(i) Initial acceleration $= \frac{32.2}{24000}(16741 - 24000 \sin 7.5^{\circ})$

$= \underline{18.26}$

(ii) First value of V_L $= \sqrt{(77.3)^2 + 2 \times 18.26 \times 400 \times 15 \times \frac{\pi}{180}}$

$= \underline{98.99}$

(iii) Average V $= \frac{1}{2}(98.99 + 77.3)$

$= \underline{88.15}$

Second acceleration

$$= \frac{32.2}{24000}\left[16741 - 24000 \sin 7.5^{\circ} - \frac{24000}{40} \quad \frac{88.15^2}{400 \times 32.2} + \cos 7.5^{\circ}\left(1 - \frac{17000 \sin 10}{24000}\right)\right]$$

$= \underline{17.07}$

Recalculating $V_L = \sqrt{77.3^2 + 2 \times 17.07 \times 104.7}$

$= \underline{97.72}$

New mean V $= \underline{87.51}$

Third acceleration, calculated by substituting 87.51 for 88.15 in Equation (3), is found to be

$\underline{17.08}$

Final calculation of V_L gives $\underline{97.73}$

This process lends itself to solution by a simple program and are devised for calculating the entry speed for a stated launch speed is shown overleaf.

```
        LIST SKID
      MASTER CALCULATE
      INTEGER WEIGHT,ANGLE,RADIUS
      WRITE(2,90)
         WRITE(2,91)
      WRITE(2,92)
      WEIGHT=20000
      ANGLE=30
      RADIUS=160
      LAUNCH=70
      A=ANGLE*3.142/180.0
      B=32.2*(18910-WEIGHT*SIN(A/2))/WEIGHT
      N=1
      C=LAUNCH**2-2*B*A*RADIUS
      IF(C.LE.0.0)GO TO 77
      SPEED=SQRT(C)
      IF(N.EQ.3)GO TO 100
      D=(SPEED+LAUNCH)/2
      E=D**2/(RADIUS*32.2)
      F=E+COS(A/2)*(1-3334/WEIGHT)
      G=F*0.025*WEIGHT
      B=32.2*(18910-WEIGHT*SIN(A/2)+G)/WEIGHT
      N=N+1
      GO TO 8
 00   WRITE(2,200)WEIGHT,ANGLE,RADIUS,LAUNCH,SPEED
 7    LAUNCH=LAUNCH+10
      IF(LAUNCH.LE.110)GO TO 5
      WRITE(2,300)
      RADIUS=RADIUS+20
      IF(RADIUS.LE.200)GO TO 4
      WRITE(2,300)
      ANGLE=ANGLE+10
      IF(ANGLE.LE.40)GO TO 3
      WRITE(2,300)
      WEIGHT=WEIGHT+1000
      IF(WEIGHT.LE.23000)GO TO 2
      WRITE(2,300)
90    FORMAT(10X,'RAMP START SPEEDS FOR SKIJUMP',/)
91    FORMAT(10X, WEIGHT    ANGLE    RADIUS   LAUNCH    SPEED )
92    FORMAT(10X,  LBS       DEG        FT      F/S        F/S )
200   FORMAT(11X,I5,5X,I2,8X,I3,4X,I3,6X,F5.2)
300   FORMAT(/)
      STOP OK
      END
      FINISH
10.33.23←
```

LINEAR APPROXIMATION FOR ENDSPEED CALCULATION

While a method of calculating endspeeds following acceleration around a curve has been introduced, it is nevertheless convenient to treat a shallow skijump as being similar to a flat deck when working to a first approximation, applying a correction factor if necessary.

The validity of this approach can be illustrated for the range of values with which this Paper is concerned by h the following examples:

Consider a skijump deck of projected length 250 ft, exit angle 15^o and path radius 400 ft.

Projection of curved portion = 400 Sin 15 = 103.5 ft

Length of curved portion = $400 \times 15^o \times \frac{\pi}{180}$ = 104.7 ft

Length of straight deck = 146.5 ft

It is intended to compare the speed achieved off a skijump launch with that off a flat deck launch.

Example 1

Aircraft weight = 24000 lb, thrust = 17000 lb
Horizontal acceleration, using method of Annex A

= $\underline{21.13 - 0.019V}$

Ignoring the momentum drag term initially:-

Speed at end of straight deck = 78.7

Allowing for average momentum drag,

Corrected acceleration = $21.13 - \frac{1}{2}(0.019 \times 78.7)$
= 20.38

Speed at end of flat deck is now 77.3

Using method illustrated earlier

Speed off ramp = $\underline{97.73}$

Speed off 250ft flat deck=$\underline{100.9}$

Example 2

Aircraft weight = 20,000 lb, thrust = 17800 lb
Acceleration on flat = $\underline{26.79 - 0.023V}$

Speed at end of straight deck = $\underline{88.6}$

Corrected acceleration = $26.79-\frac{1}{2}(0.023 \times 88.6)$
= 25.77

Corrected speed at end of straight deck = $\underline{86.9}$

Speed calculated off ramp = 110.9

Speed off 250ft flat deck = 113.5

Thus for practical purposes it can be seen to be adequate to estimate the speed off the ramp by calculating the speed as if the deck were flat and reducing it by 3%. This has been done for the further example in the text.

ANNEX C TO PART 3

```
      MASTER PROG
C     SKIJUMP-ROCKET ASSISTANCE
C     MAIN CALCULATION
      INTEGER WEIGHT,ANGLE,ROCKET
      WRITE(2,98)
       RITE(2,100)
      WRITE(2,103)
1     ROCKET=3100
      WEIGHT=20000
2     JET=50
3     ANGLE=20
4      LAUNCH=10
33     CONTINUE
5     A=ANGLE*3.1416/180.0
6     B=JET*3.1416/180.0
7     U=LAUNCH*COS(A)
8     V=LAUNCH*SIN(A)
      T=0.01
9     W=ATAN(V/U)
      C=SQRT(U**2+V**2)
      X=3.22*(19200*COS(W+B)-(0.1343*V+0.0269*u)*C+ROCKET*COS(W))/WEIGHT
      Y=3.22*(19200*SIN(W+B)-WEIGHT+(0.1343*u-0.0269*v)*C+ROCKET*SIN(W))
     1/WEIGHT
      U=U+X
      V=V+Y
      IF(v.LE.5.0)GO TO 18
       F(Y.GT.0.0)GO TO 20
      T=T+0.1
      GO TO 9
18    LAUNCH=LAUNCH+1
19     GO TO 33
 20   WRITE(2,200)ROCKET,JET,ANGLE,LAUNCH,T,U,V
      ANGLE=ANGLE+10
       IF(ANGLE.LE.20)GO TO 4
77    JET=JET+5
      IF(JET.LE.60)GO TO 3
      WRITE(2,300)
      ROCKET=ROCKET+1000
      IF(ROCKET.LE.4000)GO TO 2
98    FORMAT(10X,'JETPIPE FIXED --ROCKET ASSISTANCE',/)
100   FORMAT(10X,'ROCKET  JET   ANGLE  LAUNCH       T     U     V')
103   FORMAT(10X,'  LBS.    EG.    DEG.     F.S.      SEC    FT/S  FT/S')
 300    FORMAT(/)
200   FORMAT(11X,I5,3X,I2,3X,I3,3X,I5,4X,F5.2,2X,F5.1,2X,F5.2)
      STOP OK
      END

      FINISH
16.39.39←
```

ANNEX D TO PART 3

CALCULATION OF TOTAL SKIJUMP PERFORMANCE

1. Methods Used

a. Endspeeds required for launch

Endspeeds were calculated using Program SKIM for conditions as follows:

Weight = 20000 lb increasing to 25000 lb in steps of 500 lb

Thrust = 20000 lb

Exit Angle = 15°

Nozzle Angle= 55°

b. Acceleration along the deck

It was assumed the thrust loss due to recirculation is 2000 lb, (leaving a nett Thrust of 18000 lb), and that the jet inclination on deck is 10° down.

Then

$$\frac{W\dot{V}}{g} = 18000 \cos 10^{\circ} - 14.5V - 0.025(W - 18000 \sin 10^{\circ})$$

Hence $\dot{V}$

c. Deck lengths required

The linear approximation of a difference of 3% between speed of a skijump and speed off a flat deck was employed, i.e. the required end speed was scaled up by 3% and the distance calculated accordingly.

d. VTO weight

VTO weight was taken as 20,000 ÷ 1.15 lb

$\simeq$ 17,400 lb

e. VTO payload

VTO payload was taken as VTO weight - 12000 lb

= 5400 lb.

RESULTS

Weight	Endspeeds	Excess over VTO wt %	Payload increase %	Accel
20,000	60	15	48	27.16
20,500	70	18	57	26.33
21,000	80	21	67	25.61
21,500	89	24	76	24.89
22,000	98	26	85	24.21
22,500	107	29	94	23.57
23,000	116	32	104	22.94
23,500	124	35	113	22.36
24,000	132	38	122	21.80
24,500	140	41	131	21.26
25,000	148	44	140	20.75

Weight	Min.Distance to achieve endspeeds		
	Zero Wind	15 knot wind	30 knot wind
20,000	70	33	
20,500	99	43	
21,000	133	65	
21,500	169	91	39
22,000	210	120	58
22,500	258	155	81
23,000	311	196	110
23,500	365	238	140
24,000	424	284	175
24,500	489	336	214
25,000	560	393	258

THE EMPLOYMENT OF JET V-STOL AIRCRAFT AT SEA

PART 4

AVAILABILITY

SUMMARY

In order to put a figure to aircraft Availability it is necessary first to quantify both the supporting parameters of Reliability and Maintainability. While both of these are the subjects of rigorous definitions and study, (presumably with the continuing objective of bringing about Availability improvements), Availability itself remains only loosely defined and poorly understood.

The definitions of Availability in current use are discussed and put to the twin tests of meaningfulness and consistency, and by means of a simple simulation program a workable definition of Availability is established in terms of both the parameters already mentioned together with the intended flying programme. An alternative approach, that of calculating operational readiness is also discussed and found to produce results which compare favourably with values of availability obtained more formally.

The misgivings of the US Navy about the Availability they could expect from the AV-8A are examined and found to be largely without foundation.

Values of Reliability and Maintainability appropriate to the Sea Harrier are obtained and the dependence of Availability on both of these is examined for operation of detachments of up to four aircraft.

'When I use a word,' Humpty Dumpty said in rather a scornful tone, 'it means just what I choose it to mean -neither more nor less.'

'The question is,' said Alice, 'whether you can make so many words mean so many different things.'

'The question is,' said Humpty Dumpty, 'which is to be Master, that's all.'

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APPENDICES

INTRODUCTION

Many parameters are used to describe the operation of aircraft. Some, like speed, takeoff run, payload, can be defined in absolute engineering terms and are wholly without ambiguity. They are measured in universally agreed units and the conformance of the aircraft to the standard specified can be demonstrated and proved, to the agreement of manufacturer, procurer and customer alike. Others, while no less vital, are not so precise in their definition. These are Reliability, Availability and Maintainability. Achievement of high standards of all of these three is just as desirable as in the physical measures of performance, but no really hard and precise definitions exist for them. Everybody knows what the words mean, but in spite of lip-service being paid to the elaborate definitions which adorn them in the world of textbooks and military specifications, nobody has ever agreed unequivocally on how to measure them.

Of these latter three parameters, that of Availability is perhaps the easiest to demand. It is also the easiest to quantify. Unfortunately it is at the same time the easiest to misinterpret.

In this section, the various means by which attempts are made to quantify availability are discussed and their respective relevance to the problem in hand, that of the operation of detachments of small, possibly single-unit, detachments is explored.

MEASUREMENT OF AVAILABILITY FOR THE USER

Attempts are made to quantify availability by operators at both ends of the management spectrum. At one end is the Operations Research scientist trying to optimise his model of a defence system; at the other is the Operational Commander who wants to know how many aircraft he can have.

No definition of Availability has yet been refined that means the same to both, or even attempts to convey the same information to both.

The task of the Operations Research scientist is to evaluate the solutions to a problem of Defence. This problem will be presented to him in the form of a defined and quantified threat. His job is to counter that threat. His solution will be couched in terms of saturation, kill probability and the like and it will form the foundation stone of a Staff Requirement for a Weapon System. On the way to this solution he will have examined all the tradeoffs between, say, lots of little aeroplanes with little bombs, or one big aeroplane with a big bomb, fighters with superb radar and indifferent missiles and fighters with indifferent radar but superb missiles.

The tools of availability which he employs will be those expressly suited to his own task. As such, they are not those appropriate to the Operational Commander and his staff. This limitation is nothing like as widely appreciated as it ought to be.

The Operational Commander, for his part, already has the weapon system at its deployment station and simply wants to know how many aircraft he can expect to be able to call upon. (He might not be immediately aware of the mathematical implications of his further, usually mistated, requirement, which is to know too, how much confidence he can place in the answer he is given.)

Availability Reporting in World War II

During the Second World War the requirement for an availability measure to be fed to C-in-C Bomber Command was met by a very simple procedure. Each day, at a scheduled time, say 9am or noon, every Royal Air Force Station in the Command reported to its Group Headquarters how many aircraft it expected to be able to make available to fly that night. When all availability reports were in then the Command was in possession of a first figure on which to base the size of the offensive raid they could mount. Inevitably this figure would vary a bit as aircraft which it had been hoped would be made ready to fly failed to make it and others which had not been expected to come serviceable made it after all. But in general, this system served its purpose well and examples of the boards on which the daily tally was kept are on display at the Royal Air Force Museum at RAF Hendon. The Commander-in-Chief had not only a figure from which he could decide the next step in his strategy, but also a performance index by which he could monitor which aircraft types and individual stations under his Command produced results consistently better than the average and which ones lagged behind. The system worked and the reason why it worked well and without room for serious misinterpretations was that it was based on a one-off measurement to fulfill a one-off task.

If the task is one of continuous operation, one which is to be repeated at irregular intervals, however, the problem of supplying a figure to describe Availability is nothing like as easy. It is not unfair to say that the Operational Commander is not totally certain of what he really wants, nor are the operational units which report to him totally sure of what they ought to give him.

The Requirement

The Operational Commander seeks to learn some figure from which he can gauge the state of serviceability, or better, the state of readiness of the aircraft of his fleet. He knows from experience that whatever measurement is used a very reliable aircraft will return a figure of 80-90%, which he can interpret as implying that the aircraft is almost always available, and he knows too that a complicated aircraft recently introduced into service and not yet free of teething troubles will return a figure of 20%-30% which tells him that "a few are available now; given enough notice you can have some more, but once they have been flown we will be back to a few again". Quantifying and interpreting these extreme cases is not too difficult, but what is an Operational Commander to make of a figure that swings from one to the other and back again? Availability figures produced using current reporting procedures in use in the Fleet do just that.

Reporting Availability in the Fleet

In the days of the fixed-wing aircraft carrier there were two methods in use whereby attempts were made to record and report the current aircraft availability state. Neither one stands up to close examination, and the lessons inherent in the shortcomings of both systems while appreciated were never really learned.

Method a. The 'Mayfly'

This mode of reporting is a direct descendant of the method developed in World War II. Every day at some set hour, usually 0900, each Squadron would file a Mayfly report listing the status of its aircraft under headings such as "Serviceable now", "Expect Serviceable in 4/8/12 hours' time, "Expected to remain unserviceable for 12 hours or more".

While this report would have been adequate for the purpose of aiding a Command in planning an operation such as a mass raid, its suitability as a management aid in a more flexible operational context leaves a lot to be desired.

The main shortcoming of this system of reporting is, of course, that it attempts to use the results of a spot check, and not even a random one at that, to give a picture that will depict the status for the whole day. The aircraft reported flying and serviceable at 0900 could well be all unserviceable by 1000, and likely to remain so, and their successors in the flying programme which had been serviceable on deck at 0900 might be hopelessly unserviceable by the time they had recovered from their first flight two hours later. Or the squadron might be having a good day and the aircraft would reamin serviceable throughout. Although statistical means existed for putting values to these probabilities, they were never employ.ed

While staff and squadrons alike were fully aware of the weaknesses of this system of reporting, its use persisted, and the daily reports were dutifully logged and returned to Higher Command who actually took them into account when assessing the performance of their aircraft and operators. Naturally too it was known to be in a Squadron's own interest to return as optimistic a picture as possible, secure in the knowledge that the likelihood of their being called to account was fairly remote.

Method b. Continuous Recording

In this system a continuous record was maintained of the serviceability state of each aircraft while the ship was at Flying Stations. A bar chart was filled in, hour by hour, throught the whole period, times that the aircraft was serviceable being left blank while interludes of unserviceability were blocked in in red or black. At the end of the flying day, the total proportions of time spent unserviceable for all aircraft reported on was subtracted from 100%, and the result entered as the Availability for that day.

This system was slightly better than the 'Mayfly' system in that an attempt was at least made to evaluate a figure for availability by continuous recording rather than by a spot check, but its biggest drawback was that any relationship the result might bear to any measure of maintenance achievement worked in the opposite sense to that intended. A high success rate of sorties flown could be accompanied by a low measure of Availability if the aircraft had to spend the time between sorties being worked on because of unserviceability, and also, as happened when no flying could go on at all because of unserviceability of the ships catapults, a very impressive figure for Availability would result, simply because the aircraft never had a chance to go unserviceable.

Neither of these methods of measuring Availability was much use as a means of deriving either a true record of performance or a basis on which to form requirements for availability of aircraft of the next generation. The lack of credibility of information in availability returns coming from reports of this kind was, of course, generally acknowledged. In the experience of the writer, a daily return of Availability of 90% was never an occasion for praise, nor did a return of 20% provoke alarm or censure, but all the same, the feeling of unease remained that while these figures continued to be called for, some notice of some sort was being taken of them.

The output that mattered, of course, was the figure for achievement, and this was measured against the task set. An achievement of 100% did not necessarily require availability to have the same value.

For a measurement of Availability to be valid, then, two factors need to be considered in addition to the results of spot checks or hourly checks on serviceability. These factors are:

a. The period over which Availability is called for

b. The flying task called for.

The effects of these form the subject of the bulk of the remainder of this paper.

THE CLASSICAL EQUATIONS FOR AVAILABILITY

Most treatises on Reliability, Availability and Maintainability introduce the subject of Availability with a formula similar to the following:-

$$\text{Availability} = \frac{\text{Uptime}}{\text{Uptime + Downtime}}$$

If Downtime is to be taken as being solely the repair time due to defect rectification, then it can be calculated as the product of:-

a. The number of defects to be rectified, which is in turn the Operating Time x The Defect Rate, and

b. The mean time to repair each defect.

$$\text{So, Availability} = \frac{\text{Uptime}}{\text{Uptime} + \dfrac{\text{Uptime}}{\text{Mean Time Between Defects}} \times \begin{array}{l}\text{Mean Time}\\ \text{to Repair}\end{array}}$$

which reduces to

$$\text{Availability} = \frac{\text{MTBD}}{\text{MTBD + MTTR}}$$

This definition is normally, and rightly, qualified with the caveat that it applies only to continuous processes such as Power Generation, where the system operates only in the two states of being serviceable and on line, and being unserviceable and undergoing repair. Once repair has been completed it will go straight back on line again. However, this proviso notwithstanding this definition has tended to become fixed in people's minds as being applicable to any process in which downtime due to unserviceability is known to cause a problem.

Immediately, two interpretations become possible. Is 'Downtime' limited in content solely to that time off line due to defect rectification? If so, then other possible contributors to Downtime such as scheduled maintenance are ignored. Is 'Uptime' intended to mean 'time actually running' or 'time when the system could have been run if required'? The answers come totally differently in each case, and the possibility of confusion, followed by mistrust and disbelief, begin to increase.

The constituent part of Unavailability most noticeably out of the control of the operator is the amount of time out due to defect rectification, so it is the effect of this that he is most anxious to measure. An accepted version of the Availability equations, and one considered appropriate to aircraft operations, then becomes:

$$\frac{(\text{Total Time - Defect Rectification Time})}{\text{Total Time}} \times 100\%$$

This should still be limited to use in continuous operations, such as sustaining an Anti-Submarine Screen or Combat Air Patrol, but its accurate and regular presentation does serve to indicate to the Operational Commander two things after processing:-

a. How many aircraft he could hope to keep on task with what probability

b. The variation in Availability due not only to defect occurence rates but also to the rates at which they are rectified. Even if the defect rate itself is outside his control, he should be able to exercise some influence over the speed at which the defects are recovered, and hence over the adverse impact of the defect rate on the Availability picture. This subject is aired more fully in Appendix 1 to this paper.

Defect Rates - Which ones to use

Proper measurement of Defect Rates and Mean Times Between Defects is, of course, crucial to the calculation of aircraft Availability, and the process of selection of defect rates for use sets a veritable mine-field of traps for the unwary to stumble into.

The prime source of information on defect rates of aircraft of the Royal Air Force and the Royal Navy is the Maintenance Data Centre at RAF Swanton Morley. Here are gathered, stored and analysed copies of every Aircraft Job Card raised in the course of defect rectification, and from MDC regular outputs of defect rate figures are distributed periodically to Commands, Stations and other entitled formations. It is in the selection and application of these defect rates that the biggest pitfalls lie. If an inappropriate defect rate is fed into the formula for Availability, (setting aside for the moment the still unresolved question of whether the formula itself is correct for the application to which it is being put), then the wrong answers will come out, the wrong inferences drawn, and the wrong actions initiated.

How can there be a choice of Defect Rates? A Defect is a Defect; if it went wrong, it had to be fixed, surely? The answer to this problem is one of definition. A fault in an aircraft that requires unscheduled work to be carried out before the aircraft is returned to a state of serviceability is termed an Arising, not a Defect, and it is Arisings which give rise to the Job Cards which arrive at the Maintenance Data Centre. Those Arisings for which some positive remedial action needs to be carried out are then classed as Defects. The remainder, for which no corrective action was necessary, i.e. the defect was not confirmed after a test or a proving run, remain as Arisings, which as a class outnumber Defects. The size of the difference between the classes is greater than the uninitiated might suppose. Records at MDC show that about 15% of Arisings in the Avionic systems of current aircraft are unconfirmed at test. While this may appear at first sight to be a most unhappy state of affairs - are not the Aircrew being a bit too trigger-happy in placing their aircraft Unserviceable? - it should be remembered that for many aircraft the accepted Maintenance Policy for Avionics at First Line is to rectify first and ask questions afterwards. A set is changed at the first sign of trouble. That way the aircraft can be set right during the period it is on deck for refuelling and rearming. Whether workshops at Second Line confirm the defect or not is a secondary matter - the important thing is to get the aircraft flying again with the minimum of delay, and black-box changes are exercised as a form of replenishment. As an example, the MDC output for the first six months of 1978 shows the difference between the Arising Rate and the Defect Rate for the Navigation and Communication systems in the Harrier GR III to be 16%.

Standardisation is not helped by the fact that the prime military reference book, the 'NATO Glossary of Terms' does not offer a definition of the word 'Defect' at all (Nor does it define Availability).

So a difference in interpretation has been identified between Arising Rates and Defect Rates. The question now is that of deciding which defects to count when calculating aircraft availability.

Total defect rates in the regular MDC outputs cover arisings from all sources. Defects will occur in the various phases of aircraft flight, startup, takeoff, climb, etc, and these are the ones springing immediately to mind when the term Defect is introduced. But they are found also just as frequently in Flight Servicing, Flexible Servicing, Annual Surveys, during Role changes and the rest, and the dangers of taking the undefined defect rate from an MDC routine output and applying it to an exercise in the limited context of flight operations alone can now be appreciated. But it is far from unknown for Defect Rates published for one particular application to be appropriated for use in another, totally different, field of research for which they are completely unsuited.

The Defects having a direct effect on the Availability of an aircraft engaged in a continuing flying exercise are those found by Aircrew in use or by ground crew during Flight Servicing, and even these can be screened to filter out those which can be held over until the flying period is finished. The value of the defect rate remaining will inevitably be well below the overall defect rate previously considered, and so properly conducted calculations of Availability will lead to answers more optimistic than those previously arrived at by less enlightened agencies. Fortunately, the Maintenance Data System offers the facility of selective interrogation of its files of defect data, so proper and representative values for defect rates may be obtained for use in Availability calculations. This theme is developed later on Page 48 et seq.

The 'Six-Sevenths' Factor

The simple Availability formula fails to give a true picture of how much use can be got out of an aircraft, as its use assumes an aircraft to be able to fly as soon as it is ready to fly, i.e. as soon as defect rectification has been completed and signed for. In practice there are other delays experienced that eat into the time Available. Strapping in, starting-up, shutting-down, unstrapping and clearing the aircraft all take time and if the aircraft is engaged on flying short sorties, this time must have an effect on the true availability of the aircraft.

Studies on SeaKing Aircraft in HMS 'Hermes' (Ref.1) based on comparisons made between the length of time an aircraft was signed out and the true length of the sortie showed that for every seventy minutes it was signed out it flew for only one hour. So in a properly refined study, Availability as calculated from measures of Defect down-time should be factored by a further 6/7 if the realistic value is required. In current practice however, this step is not taken, but the 'six-sevenths' factor should be remembered when demands for levels of Availability greater than about 90% are being examined.

Rectification Times

The Job Cards from which we get Defect and Failure information can also be interrogated to yield values for defect rectification times. These too need to be treated cautiously because the time it took to rectify a defect will not always be the quickest time it could have taken. Sometimes a more trustworthy surrogate to use is the recorded value for man-hours, taken straight or factored.

OPERATIONAL READINESS - AN ALTERNATIVE MEASURE

'Availability' as conventionally defined has been shown to be an inadequate measure of the true availability of an aircraft as we understand the meaning of the word. Even in cases of continued operation where it is admittedly adequate to a degree, its limitations are reached if the flying exercise continues until not one aircraft is left serviceable, as the availability recorded will only be a true reflection of the state at a point halfway down a steady decline from the initial point of 100% serviceability.

What an Operational Commander requires, it is safe to presume, is some measure, not of his aircraft state right now, but of how many he could hope to field if he declared a task after a reasonable period for preparation. How many aircraft can he depend on when battle is joined?

The capability of the aircraft to be available under these terms is defined as Operational Readiness.

Availability and Operational Readiness differ in specification as follows:-

"The Availability of a system or equipment is the probability that it is operating satisfactorily at any point in time when used under stated conditions, where the total time considered includes operating time, active repair time, administrative time and logistic time".

"The Operational Readiness of a system or equipment is the probability that at any point in time it is either operating satisfactorily or is ready to be placed in operation on demand when used under stated conditions including stated allowable warning time".

Both definitions are taken from Ref.2.

In more concise mathematical terms the definition of Operational Readiness develops as follows (Ref.3).

In the simplest Model the assumption is made that if no failures develop in a preceding mission the aircraft is fully available to be called upon to fly once more. If failures do develop, the aircraft will be ready for the next mission only if the maintenance time is shorter than the time until the next launch is due. Thus:

$$P_{OR} = R(t) + Q(t) \times P(t_{maint} < t_{next\ launch})$$

where P = Probability; $R(t)$ = Reliability at time t, and $(R+Q) = 1$.

If a fixed interval between flights has been set in advance, as is usual with a day's exercise programme with no expectation of unscheduled launches being called up, the probability that an unserviceable aircraft will be ready in time for the next call may be restated simply as being the probability that the maintenance time is less than the interval between recovery and launch. As maintenance time is usually, (at least in the UK Ministry of Defence), taken to follow a negative exponential distribution about the mean, this probability will be simply an exponential function of the two.

While the Reference covers all cases of exponentially distributed times to next launch, mission duration, probabilities of extra defects coming to light on a hitherto serviceable aircraft, and offers reasonably manageable solutions for them all, this initial sortie into the mysteries of Availability and how it can be calculated will confine itself to two cases only, viz:-

a. Continuous aircraft operation, in which the aircraft flies again as soon as it is made ready

b. Programmed operations, in which the aircraft is not required to fly again until a fixed pause has elapsed since its last recovery.

A few experiments using two simple simulation models will serve to illustrate the points raised so far.

COMPARISON OF AVAILABILITY MEASURES

SIMULATION MODEL 1 - SCAP (CONTINUOUS FLYING)

Simulation models have been in use for some years for the purpose of exploring the effects and interaction of varying all the controllable parameters of aircraft operations.

Prominent among recent examples is the model devised for the United States Marine Corps for predicting the behaviour of a squadron of AV-8A Harriers. Called MOVES - Maritime Operational V-STOL Environment Simulation - it has been in regular use since 1975, and it has undergone a continuous process of development and validation against the reality of actual squadron operations so that the USMC has confidence that the responses of the model to changes in input variables is a true indication of what would happen in fact if such changes were actually brought in.

UK interest in MOVES dates from February 1977 when a team from the facility at Washington Navy Yard demonstrated their model to the Ministry of Defence. The response of the MOD was made in two stages. First, the Royal Navy bought time on the US Model in order to carry out as much forecasting as possible of the behaviour of the Sea Harrier in advance of its introduction into naval service. Then RAF Science 1 set out to develop its own corresponding model for UK use drawing on the experience of the Royal Naval involvement while it did so.

At the time of writing it can safely be recorded that the RN participation has been successful, and that is not to say that all the pre-MOVES predictions have been triumphantly vindicated. (On the contrary, in certain sections of MOD RN a lot of agonised reappraisal of earlier comfortable forecasts has had to take place). However, operation on a full-scale model simulation system tends to invite an understandable enthusiasm on the part of the operators to vary all the variables in one go, so MOVES has afforded no opportunity for more fundamental research of the sort being carried out in this Section of this study.

Therefore, in order to demonstrate the differences between the various estimators of Availability which have been considered, a simple program has been devised with the intention of investigating the performance of one aircraft operating alone, notionally from a single-unit ship.

The Model, called SCAP, has no aim more ambitious than to see how many sorties can be flown by one aircraft in the course of a day of given duration.

The variables considered are:-

Sortie length
Mean Time Between Failure
Mean Time To Repair
Duration of Flying Day.

A time for Turn-Round has been assumed to be an arbitrary 15 minutes, but this is open to variation given a simple program amendment.

The object is to measure the number of sorties achieved in the day as a proportion of the ideal number that could be achieved given zero defects. This figure, which is surely as near a definition of what Availability is thought to mean as one could get, can then be compared with the rival contestants commonly in use i.e.:-

a. Availability = MTBF / (MTBF + MTTR)

b. Availability = (Total Time - Downtime) / Total Time

c. Operational Readiness = P(S) + P(U/S) X P(ready by next call)

The model works to the following sequence of rules:

a. The aircraft, which starts the day in a serviceable condition, is flown for a length of time = CAP

b. The probability of it returning fully serviceable is taken to be the Survival Probability:

$$R = \mathrm{Exp}(-\ CAP/MTBF)$$

c. A pseudo-random number is generated (see Appendix 2)

d. This is compared with R. If it is less, then the aircraft is deemed to be Serviceable in which case the time is advanced by the length of a Turn-Round Servicing operation, in this case 15 minutes. If it is greater, the aircraft is Unserviceable, and a further pseudo-random number is generated to determine the length of the downtime, such that:-

$$\text{Pseudo-random} = \mathrm{Exp}(-T/MTTR)$$

If T is less than 15 minutes, the running time is advanced by 15 minutes (i.e. the Turn-Round servicing takes longer than the rectification). If more, the running time is advanced by T. If it exceeds the time remaining for the flying day, then the day's flying is complete, and the Downtime is taken as being equal to the time remaining in the day.

e. If time permits, the aircraft is flown again on a sortie of length CAP, and the cycle repeated until the day is exhausted.

f. The program runs for 100 days and the results averaged to give the following data:-

Average number of flights per day
Average time unserviceable

Average Availability $(= (1 - \frac{\text{Average Time Unserviceable}}{\text{Length of Day}})$

g. The whole sequence is then rerun, the values of the variables being adjusted as required.

The artificialities of the exercise lead to the following "Ground Rules" having to be applied:

a. Availability is measured only over the duration of specified flying day

b. If there is time to launch an aircraft before (but not at) the end of the day it will be launched, even though the flight time will extend beyond the end of the day and hence the time unserviceable, if any, will not contribute to the 'Availability' calculation at all

c. All defects are assumed to have been rectified overnight.

Rules a and b do no more than conform with current practice in the measurement of Availability at sea, and Rule c, while optimistic in engineering terms is not unduly so.

This can be confirmed as follows:

Assume the last aircraft took off at the very end of a flying day of 12 hours duration to fly for one hour.

It has 11 hours to recover from any defect.

If the MTTR is taken as 4 hours, the probability of the aircraft still being unserviceable at the time of the first launch of the following day is the survival probability:-

$\mathrm{Exp}(-11/4)$

$= \underline{6.4\%}$

which is considered to introduce no more inaccuracy than that inherent in the assumptions of the nature of the distributions of the defect occurrence and downtime. (The MTTR of 4 hours is, if anything, slightly pessimistic. The value employed in the RN MOVES exercise is 3.91 hours).

CAP values were taken as 60 and 80 minutes. These are durations appropriate to the Harrier GR III, and are calculated from the Operating Data Manual (Ref.4), the detail being shown in Appendix 3.

SIMULATION MODEL 2 - SCAR (PROGRAMMED FLYING)

This Model differs from its companion only insofar as the flying programme depicted is not simply one in which the aircraft flies again as soon as it can after the previous sortie.

The programme now is one in which the aircraft is scheduled to fly again after a fixed interval from its time of landing provided that it is not still unserviceable at the time for the next launch. If it is late for the launch the trip is cancelled, and that turn is missed altogether. This represents an exercise program during a ship's workup period, or alternatively a Combat Air Patrol duty shared among two or more single-unit ships. It is shown at Appendix 4.

Results 1 - Continuous Flying (SCAP)

The output results are summarised in Tables 1-4, while Achievement, (= Sorties Launched - Sorties Planned), Availability as MTBF ÷ (MTBF + MTTR), and Operational Readiness are shown graphically against MTBF in Figures 1-4. (Availability as (1 - Downtime/Day length) has been omitted from these plots for the sake of clarity).

All cases cover a flying day of 12 hours duration, and sortie lengths of 60 minutes and 80 minutes. These values are representative of actual values for the Sea Harrier, as is the value of 240 minutes for Mean Time To Repair.

Observations

a. Measures of Availability - Which one to trust

These results enable a realistic look to be taken at the respective merits of the estimates of Availability that have been considered so far.

(i) Achievement

This is measured as a post hoc record of what the aircraft actually did compared with what it had been tasked to do. It is the yardstick against which the other evaluations are to be compared. The maximum number of sorties possible has been taken as being the maximum number that could be launched in the day, not the number that could be completed.

Thus part-sorties have been considered as being whole sorties, the divisor in evaluating Achievement is, in some cases, slightly higher than a pure calculation would use, and in such cases the result can be regarded as a slight understatement of the true achievement.

(ii) Availability in terms of (1-Downtime/Day length)

This tallies closely with Achievement, being another value which is only calculated after flying is complete. It is included in these results in order to illustrate the difference between itself and the classic measure of MTBF ÷ (MTBF + MTTR) with which it is prone to get confused. It is inevitably higher, because it does not include defect downtime still outstanding after the flying day is completed. It is an accurate measure so long as flying is continuous, but, as will be shown later, it tends to underestimation when applied to programmed flying.

(iii) Availability in terms of MTBF ÷ (MTBF + MTTR)

This can be seen to be a hopelessly pessimistic parameter as a forecaster of Availability. The reason is that it depicts Availability in the limiting case, but flying exercises just do not keep going that long.

(iv) Operational Readiness

Operational Readiness as calculated gives the unconditional probability of making the next sortie, and hence of successfully completing the flying programme. As an estimator of Availability it can be calculated in advance given that details of MTBF, MTTR and the intended flying schedule are to hand. The minor differences between the Operational Readiness calculated and the Achievement demonstrated in these examples may be attributed to the end-effects caused by operating over a flying day of absolute length.

Clearly Operational Readiness is a far better forecasting aid than is MTBF ÷ (MTBF + MTTR)

b. Effect of Increasing MTBF

Results show that linear increases in MTBF, i.e. in Aircraft Reliability, show a diminishing return in Achievement, and it follows that for improvements in Achievement to be maintained, the rate of increase in MTBF must be geometric or logarithmic rather than linear. The relationship will be explored more thoroughly in a later section, but the point must be stressed that unreliability will

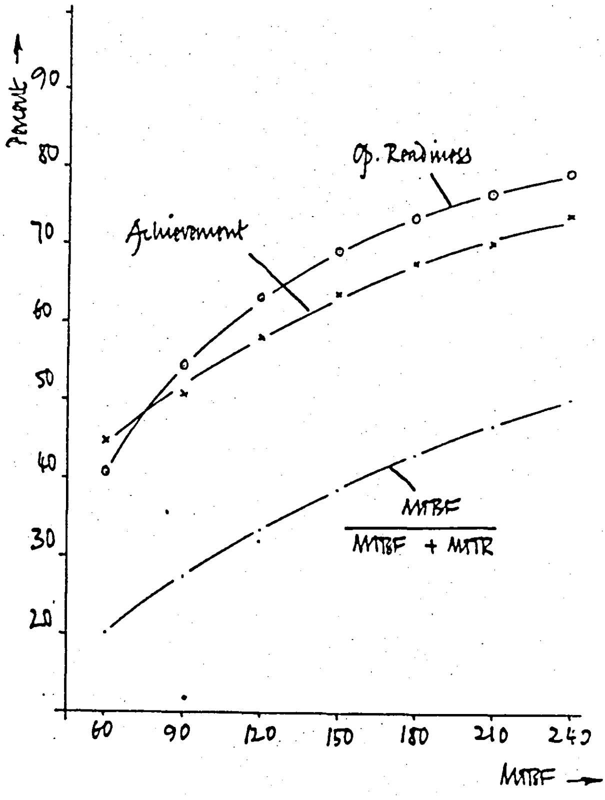
SCAP OUTPUT ANALYSIS

Day = 10 hours; Sortie length = 60
Max.Sorties = 8 ; MTTR = 240

MTBF	60	90	120	150	180	210	240
SORTIES	3.56	4.03	4.63	5.08	5.40	5.60	5.90
% SORTIES	44.5	50.4	57.8	63.5	67.5	70.0	73.8
AVAIL.	44.5	48.9	55.6	59.9	64.6	66.5	70.6
MTBF ÷ (MTBF+MTTR)	20.0	27.3	33.3	38.5	42.9	46.7	50.0
R	0.368	0.513	0.606	0.670	0.716	0.751	0.779
Q	0.632	0.487	0.394	0.330	0.284	0.249	0.221
Q x P_{tm}	0.038	0.029	0.024	0.020	0.017	0.015	0.013
O.R	40.6	54.2	63.0	69.0	73.3	76.6	79.2

TABLE 1

CONTINUOUS FLYING
Sortie = 60, MTTR = 240, Day = 10
From Table 1 :-



— Fig 1 —

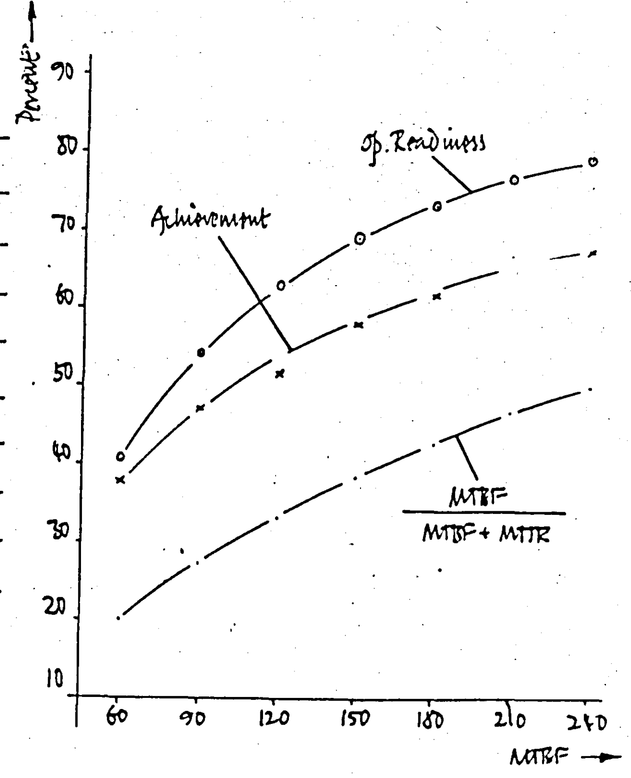
SCAP OUTPUT ANALYSIS

Day 12 hours; Sortie length = 60
Max.Sorties = 10 ; MTTR = 240

MTBF	60	90	120	150	180	210	240
SORTIES	3.79	4.72	5.17	5.82	6.18	6.68	6.71
% SORTIES	37.9	47.2	51.7	58.2	61.8	66.8	67.1
AVAIL	42.2	49.8	53.9	58.9	61.8	66.5	67.4
MTBF ÷ (MTBF+MTTR)	20.0	27.3	33.3	38.5	42.9	46.7	50.0
R	0.368	0.513	0.606	0.670	0.716	0.751	0.779
Q	0.632	0.487	0.394	0.330	0.284	0.249	0.221
Q x P_{tm}	0.038	0.029	0.024	0.020	0.017	0.015	0.013
O.R	40.6	54.2	63.0	69.0	73.3	76.6	79.2

TABLE 2

CONTINUOUS FLYING
Sortie = 60, MTTR = 240, Day = 12
From Table 2 :-



— Fig 2 —

SCAP OUTPUT ANALYSIS

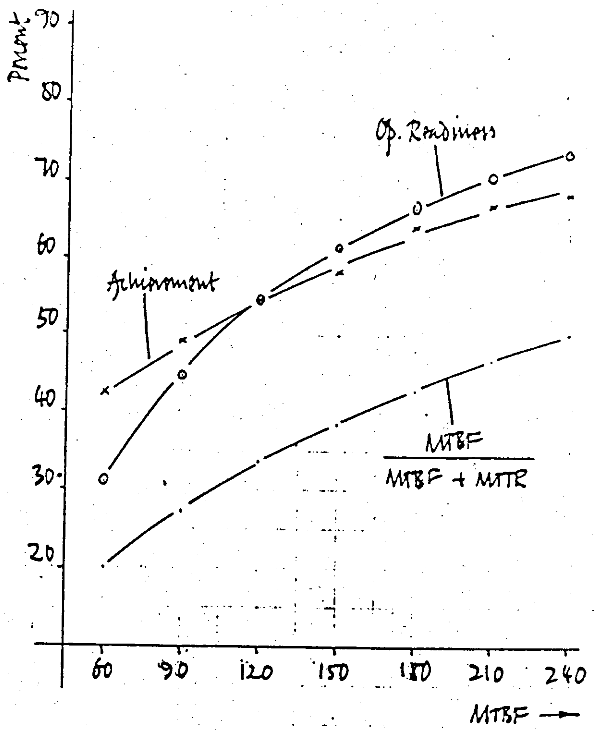
Day = 10 hours; Sortie length = 80

Max.Sorties = 7 ; MTTR = 240

MTBF	60	90	120	150	180	210	240
SORTIES	2.97	3.44	3.82	4.07	4.48	4.67	4.77
% SORTIES	42.4	49.1	54.6	58.1	64.0	66.7	68.1
AVAIL	46.4	51.7	57.1	60.6	67.1	68.7	70.4
MTBF ÷ (MTBF+MTTR)	20.0	27.3	33.3	38.5	42.9	46.7	50.0
R	0.264	0.411	0.513	0.587	0.641	0.683	0.716
Q	0.736	0.589	0.487	0.413	0.359	0.317	0.284
Q x P_{tm}	0.044	0.036	0.029	0.025	0.022	0.019	0.017
O.R	30.8	44.7	54.2	61.2	66.3	70.2	73.3

TABLE 3

Sortie = 80, MTTR = 240, Day = 10
From Table 3:-



— Fig 3 —

CONTINUOUS FLYING
Sortie = 80, MTTR = 240; Day = 12
From Table 4:-

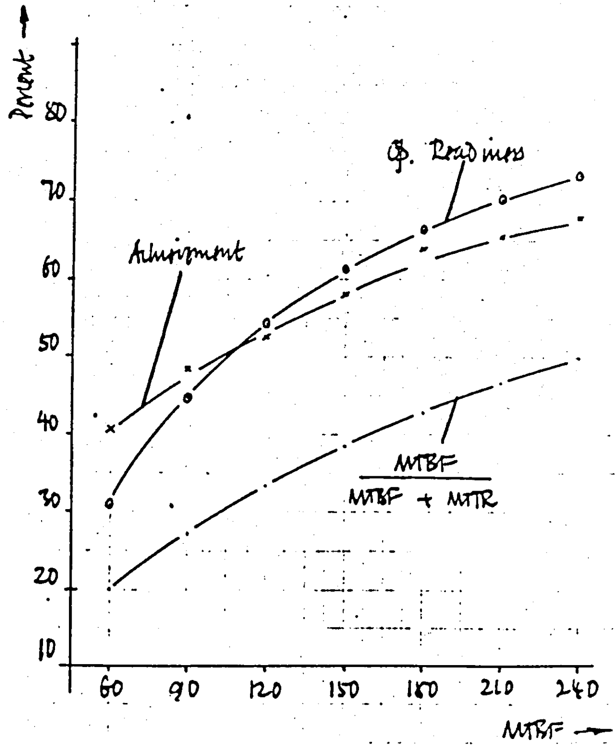
SCAP OUTPUT ANALYSIS

Day = 12 hours; Sortie length = 80

Max.Sorties = 8 ; MTTR = 240

MTBF	60	90	120	150	180	210	240
SORTIES	3.23	3.87	4.20	4.65	5.13	5.23	5.45
% SORTIES	40.4	48.4	52.5	58.1	64.1	65.4	68.1
AVAIL.	44.8	50.5	54.8	59.4	65.4	65.5	68.2
MTBF ÷ (MTBF+MTTR)	20.0	27.3	33.3	38.5	42.9	46.7	50.0
R	0.264	0.411	0.513	0.587	0.641	0.683	0.716
Q	0.736	0.589	0.487	0.413	0.359	0.317	0.284
Q x P_{tm}	0.044	0.036	0.029	0.025	0.022	0.019	0.017
O.R	30.8	44.7	54.2	61.2	66.3	70.2	73.3

TABLE 4



— Fig 4 —

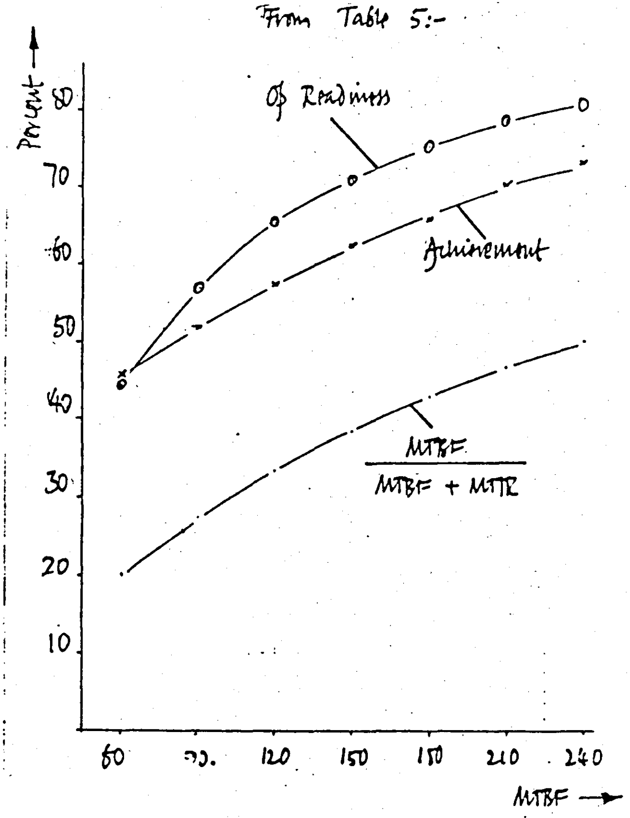
SCAR OUTPUT

Day = 12 hours;
Sortie = 60
Max.Sorties = 8
MTTR = 240
Pause = 30

MTBF	60	90	120	150	180	210	240
SORTIES	3.67	4.16	4.60	4.99	5.25	5.61	5.84
% SORTIES	45.9	52.0	57.5	62.4	65.6	70.1	73.0
AVAIL %	45.7	52.1	57.6	62.1	65.9	69.9	72.6
MTBF / MTBF+MTTR %	20.0	27.3	33.3	38.5	42.9	46.7	50.0
OR %	44.2	57.0	65.2	70.9	74.9	78.0	80.5

TABLE 5.

PROGRAMMED FLYING
Sortie = 60, MTTR = 240, Day = 12
Pause = 30
From Table 5:-



— Fig 5 —

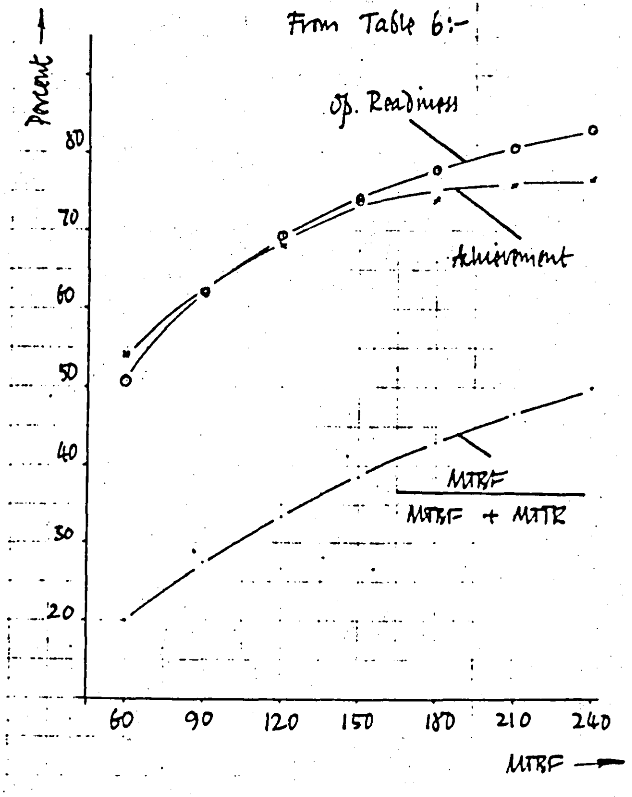
SCAR OUTPUT

Day = 12 hours;
Sortie = 60
Max.Sorties = 6
MTTR = 240
Pause = 60

MTBF	60	90	120	150	180	210	240
SORTIES	3.24	3.70	4.08	4.43	4.39	4.54	4.58
% SORTIES	54.0	61.7	68.0	73.8	73.2	75.7	76.3
AVAIL %	48.0	56.8	62.8	69.8	70.3	72.3	73.4
MTBF / MTBF+MTTR %	20.0	27.3	33.3	38.5	42.9	46.7	50.0
OR %	50.8	62.1	69.3	74.3	77.9	80.6	82.9

TABLE 6

PROGRAMMED FLYING
Sortie = 60, MTTR = 240, Day = 12
Pause = 60
From Table 6:-



— Fig 6 —

continue to be a problem even though Reliability be increased to unheard of dimensions. While a finite chance exists of a downing defect occurring, the chance exists too of missing the next sortie, with all that such a failure might entail.

Even a success rate as modest as 90% for a days flying of six sorties is a lot to ask for, if only a very low interval between sorties is allowed. The Reliability (R) of an aircraft on a 60 minute sortie must be such that

$$R^5 = 0.9, \quad \text{whence } R = 0.979,$$

so the Mean Time Between Failures, (M) is the solution of:

$$\text{Exp}\,(-60/M) = 0.979$$

$$\text{whence } M = 2827 \text{ minutes}$$

$$= 47 \text{ hours,}$$ which is way in excess of current values for military aircraft.

c. Effect of MTTR

In theory, the 90% success rate called for in the example above could be met given a much lower, (and more realistic) Reliability, if the MTTR was also very low. As a parameter, the Mean Time to Repair a defect is much more under the immediate control of Command than is Reliability itself. Reliability is a characteristic of the aircraft or equipment, while Mean Time to Repair contains a measure of the quality of support activity devoted to it. The relationships and interactions between the two will be looked into later.

Results 2 - Programmed Flying - SCAR

The results are summarised in Tables 5 through 10, with the pause between sorties increasing from 30 minutes to 180 minutes by 30 minute steps. Achievement, Operational Readiness and Availability as MTBF ÷ (MTBF + MTTR) are plotted in Figures 5-10.

As in the previous program, the object is to illustrate the various measures of Availability at work rather than forecast the Availability to be expected from the Sea Harrier. All the same, where numerical values are used, they are of the same order as those appropriate to the aircraft.

RESTRICTED

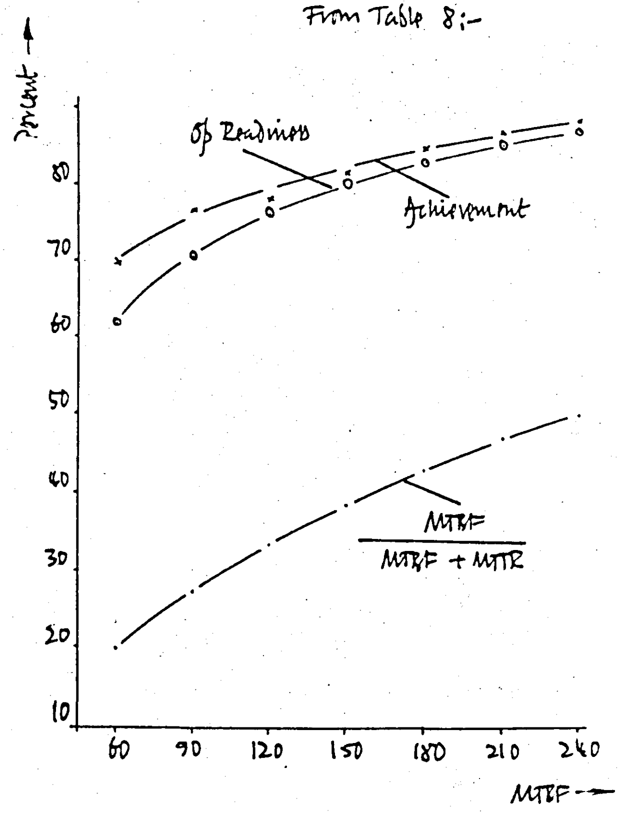
SCAR OUTPUT

Day = 12 hours; Sortie = 60
Max.Sorties = 4
MTTR = 240
Pause = 120

MTBF	60	90	120	150	180	210	240
SORTIES	2.78	3.06	3.12	3.26	3.38	3.45	3.52
% SORTIES	69.5	76.5	78.0	81.5	84.5	86.3	88.0
AVAIL	55.3	63.8	68.4	72.4	76.2	80.1	81.2
$\frac{\text{MTBF}}{\text{MTBF+MTTR}}$	20.0	27.3	33.3	38.5	42.9	46.7	50.0
OR	61.7	70.5	76.1	80.0	82.8	84.9	86.6

TABLE 8.

PROGRAMMED FLYING
Sorties = 60, MTTR = 240, Day = 12
Pause = 120
From Table 8:-



— Fig 8 —

RESTRICTED

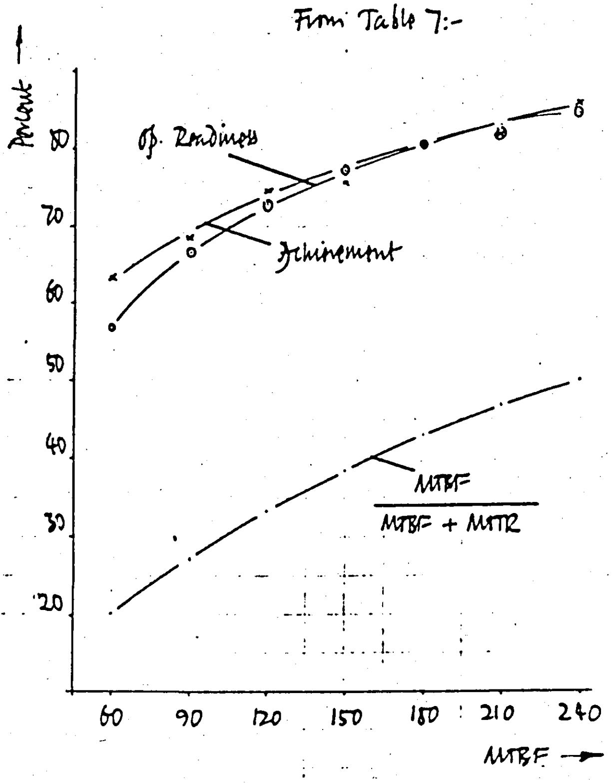
PROGRAMMED FLYING
Sortie = 60, MTTR = 240, Day = 12
Pause = 90
From Table 7:-

SCAR OUTPUT

Day = 12 hours; Sortie = 60
Max.Sorties = 5
MTTR = 240
Pause = 90

MTBF	60	90	120	150	180	210	240
SORTIES	3.16	3.43	3.74	3.78	4.03	4.10	4.31
% SORTIES	63.2	68.6	74.8	75.6	80.6	82.0	86.2
AVAIL %	53.1	59.9	66.2	69.7	74.8	76.8	81.7
$\frac{\text{MTBF}}{\text{MTBF+MTTR}}$ %	20.0	27.3	33.3	38.5	42.9	46.7	50.0
OR %	56.6	66.5	72.9	77.3	80.4	82.9	84.8

TABLE 7.



— 7 —

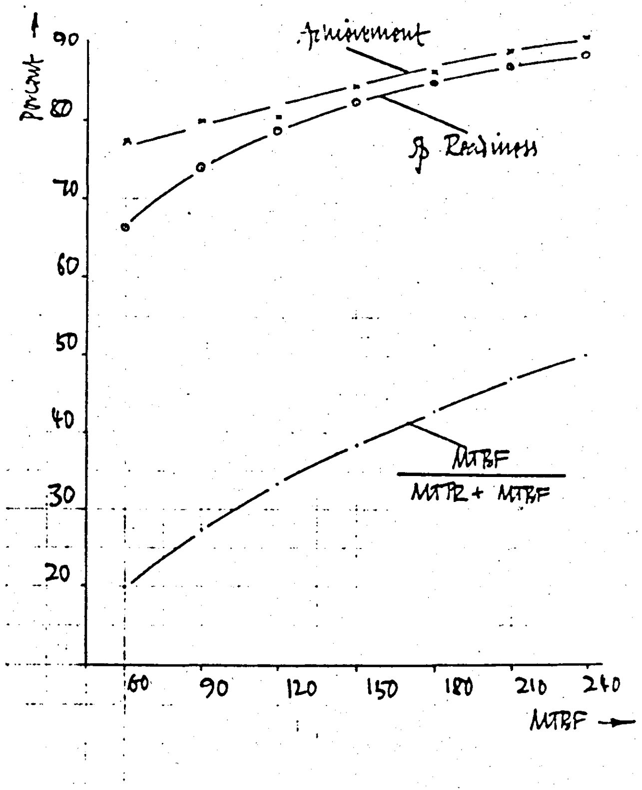
SCAR OUTPUT

Day = 12 hours; Sortie = 60
Max.Sorties = 4
MTTR = 240
Pause = 150

MTBF	60	90	120	150	180	210	240
SORTIES	3.09	3.19	3.22	3.38	3.45	3.56	3.63
% SORTIES	77.3	79.8	80.5	84.5	86.3	89.0	90.8
AVAIL	62.1	68.1	70.3	76.4	79.1	82.4	84.5
$\frac{MTBF}{MTBF+MTTR}$	20.0	27.3	33.3	38.5	42.9	46.7	50.0
OR	66.2	74.0	78.9	82.3	84.8	86.7	88.2

TABLE 9.

PROGRAMMED FLYING
Sortie = 60, MTTR = 240 Day = 12
Pause = 150
From Table 9:–



— Fig 9 —

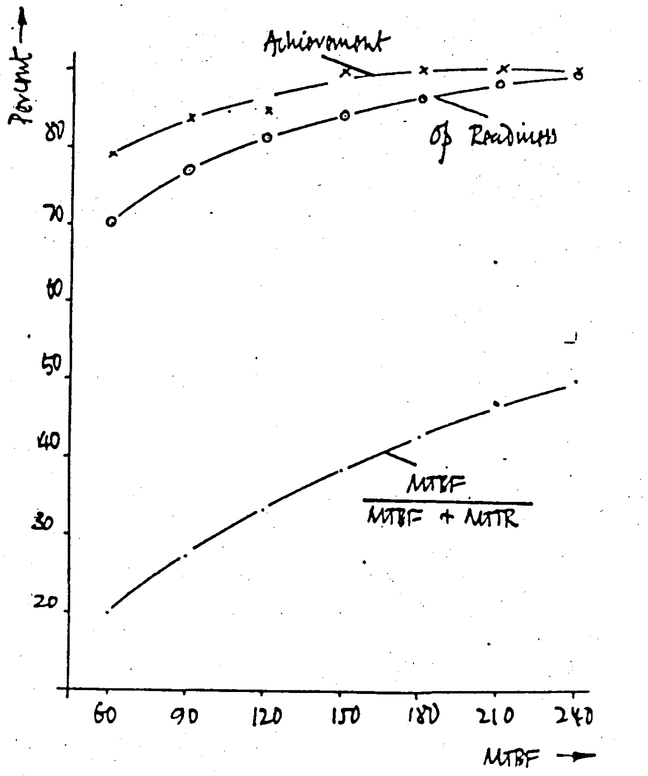
SCAR OUTPUT

Day = 12 hours; Sortie = 60
Max.Sorties = 3
MTTR = 240
Pause = 180

MTBF	60	90	120	150	180	210	240
SORTIES	2.37	2.51	2.54	2.70	2.76	2.76	2.75
% SORTIES	79.0	83.7	84.7	90.0	90.2	90.2	90.2
AVAIL %	61.1	69.9	73.5	79.1	81.8	83.9	83.2
$\frac{MTBF}{MTBF+MTTR}$ %	20.0	27.3	33.3	38.5	42.9	46.7	50.0
OR %	70.1	77.0	81.4	84.4	86.6	88.2	89.6

TABLE 10

PROGRAMMED FLYING
Sortie = 60, MTTR = 240, Day = 12
Pause = 180
From Table 10



— Fig 10 —

Observations

a. Measure of Availability

(i) Achievement

As the gap between sorties increases, the number which can be fitted into the day goes down. But the increasing gap increases the probability of a defective aircraft being rectified in time for the next sortie, so the probability of achieving the target goes up. Thus the chance of launching the 8 sorties possible with a pause between sorties of 30 minutes is only 45% when the MTBF = 60, while increasing the pause to 150 minutes improves the chances of achieving the more modest ambitions of 4 sorties to 77%. Note too that the maximum achievement becomes less and less dependent upon the value of MTBF.

(ii) Availability in terms of (1-Downtime/Day length)

This was an accurate reflection of achievement in the cases considered for continuous flying. However, as the gap between sorties is widened, it can be seen to fall further and further behind. So it can be seen that the spacing of the flying programme has an increasing influence on the chances of success, which this measure of Availability does not entirely match.

(iii) Availability in terms of MTBF ÷ (MTBF + MTTR)

The range of values of MTBF and the one value of MTTR used in this equation have remained unaltered throughout this series of simulation exercises, and so their predicted availability figures have remained steadfastly constant, totally unaffected by the variation in the flying programme happening around them. This measure of Availability is simply of no relevance to aircraft calculations of this sort.

(iv) Operational Readiness

This ties up quite well with Achievement. Only the effects of the flying day being of finite length give Operational Readiness room for error as a means of forecasting performance.

CONCLUSIONS

Availability is required to be quantified for two purposes:-

a. To record what has gone before

b. To forecast what can be done in future.

Recording

Values of MTBF and MTTR need to be recorded for performance measurement and use in any future forecasting activity. For Availability to be recorded in a way that will be of any use for future recording, ideally the flying Achievement and flying programme against which it was measured should be recorded also.

This is possibly a lot to ask. A simpler method of recording Availability is to record the parameter (1 - Downtime/Flying Day), but it must be appreciated that this will be accurate only in the case of continuous flying. For programmed flying, this parameter will understate the achievement.

Forecasting

Forecasting Availability in terms of MTBF and MTTR alone is fruitless except in rare and specialised cases.

For forecasting to be of any use these parameters must be supplemented with details of the intended flying programme and the length of the flying day. Then Operational Readiness may be calculated as being a good forecast of what is likely to happen. Best of all methods however, and the most flexible, is simulation.

AVAILABILITY - THE MISGIVINGS OF THE US NAVY

It has been shown that any quantified statement of aircraft availability that does not include some reference to the type of flying activity over which it was measured is very likely to underestimate the potential of the aircraft type being considered. The US Navy has deep misgivings about the Availability they could hope to demonstrate if they pressed on with the development of plans to operate V-STOL aircraft in small numbers from sub-capital ships, and it is possible that lack of clear definitions of what availability means might be at least a partial cause of this.

The instance referred to comes in the United States Comptroller General's Report to the Congress on the status of the US Navy's Vertical/Short Takeoff and Landing Aircraft (Ref.5).

Dated February 1978, (that is, not many months after the commencement of the USN studies of V-STOL A and V-STOL B aircraft systems), the report introduces the case for Vertical Takeoff aircraft being procured and introduced into service, acknowledges that many steps in the advancement of V-STOL technology will have to be taken to make this possible, (but concedes that these are all capable of achievement), and then draws back with untoward alarm when the subjects of Reliability, Availability and Maintainability come into discussion.

To quote from the introductory paragraph of the section in question:-

'The key to the usefulness of V-STOL is dispersion, which can only be achieved through a substantial increase over CTOL experience in reliability, maintainability and availability. The Navy's tentative goals for the reliability and maintainability characteristics of V-STOL represent a 5 to 6 fold increase over current experience. The availability goal is 1½ times greater than the current fleet experience. The Navy is assessing the potential of achieving these goals'.

After defining Reliability to be measured in terms of Mean Flight Hours between Maintenance Actions, and Availability to be the probability that a system or equipment, when used under stated conditions is an actual operational environment, shall operate satisfactorily, the Report goes on:-

'The Navy is looking for a 6.5 hour MFHBF which represents a 500% increase over the Navy's current experience.

The Navy is experiencing a 60% rate of Availability for sea-based aircraft, which is acceptable on the large Carriers with their extreme support operations. This experienced rate is not adequate for the anticipated V-STOL operations off smaller ships with limited space for spare parts storage and repair operations. The Navy's goal for V-STOL availability, however, is 90%'.

There exists a very marked contrast between this gloomy analysis that aircraft availability at present is so poor that it could not be worthwhile to dispose the aircraft at sea in smaller-than-squadron numbers, and the impressive availability figures the US Services proudly proclaim to be their achievement in practice.

Operating a flight of 6 aircraft the US Marine Corps set a new record early in 1979 by achieving a remarkable 42 sorties in the space of 2 hours 9 minutes. The average sortie length was 12 minutes and the mean turn-round time was 6.4 minutes (Ref.6.).

Obviously, it all depends on what you mean by Reliability, Availability and Maintainability.

a. <u>Reliability</u>

A value of 6.5 hours between failures as a 500% improvement over the current figure indicates the latter to be 1.09 hours. While this might be true if all defect arisings are taken into account, it is surely pessimistic if failure is taken as meaning 'malfunctions in flight which must be rectified if the aircraft is to continue with the next sortie with a full operational capability'.

The Mean Flying Hours Between Arisings for the RAF Harrier GR III is currently running at a value of 0.62, which of course takes into account every shortcoming whether found in flight or at third line. At the other end of the scale, the Mean Flying Hours between Operational Effect Defect is 15.7, which is healthily clear of the US Navy ambitions of 6.5. So it may well be that US aircraft are nearer their Reliability goal than is thought.

b. Availability

The figure quoted in the Reference is 0.6. As has been shown, whatever an Availability of 0.6 may mean, one thing it does not mean is that the operator can expect to achieve only 60% of his planned sorties. Let a further example illustrate this point. Assume an aircraft is tasked to fly for one hour out of every three. The other two are spent undergoing rectification. It can achieve its planned sorties, so its Achievement rate is 100%. But its Availability is only 33%.

Reading between the lines of the report to Congress it does seem that the most pessimistic interpretation has been placed on this figure of 0.6, and that the true state of affairs may be nothing like as bad.

An Availability quoted baldly as 0.6, without any reference to flying task or other data can come from one of two sources:

a. Availability measured as (Day - Downtime)/Day

b. Availability measured as (MTBF)/(MTBF + MTTR)

a. Availability measured as (Day - Downtime)/Day

This measurement of Availability = 0.6 could have been extracted from Squadron records. As has been shown in the simple example above there need be no direct relationship between Availability measured in this way and Achievement.

As may be seen from Figs 1, 2, 3 and 4 the relationship is quite close in conditions of continuous flying as is shown in Table 11.

Achievement for Availability = 80%

Figure	1	2	3	4
Achievement %	69	60	57	60

TABLE 11

However, once the flying pattern changes from continuous to periodic, the relationship begins to diverge, as shown in Table 12, derived by extrapolation from Tables 5-10.

Achievement for Availability = 60%

Table	5	6	7	8	9	10
Achievement %	60	66	69	73	75	78

TABLE 12

b. Availability measured as MTBF/(MTBF + MTTR)

The interpretation of Availability = 0.6 measured by this definition is:-

$$\frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = 0.6$$

i.e. MTBF = 1.5 x MTTR

Holding MTTR at 240 minutes, as in the SCAP and SCAR program runs already executed, and setting MTBF at 1.5 x 240 = 360 minutes, (in reality a respectably high value), the programs were run again. The value of 'predicted sorties' is taken as being that resulting from the postulated US interpretation of the application of the Availability value, namely 0.6 x the number of sorties scheduled.

Results (i) Continuous Flying

Sortie	Day	Predicted	Achieved
60 minutes	10 hour	4.8	6.51
	12 hour	6.0	7.95
80 minutes	10 hour	4.2	5.29
	12 hour	4.8	6.13

Results (ii) Programmed Flying

Pause	Predicted	Achieved
60 minutes	3.6	5.08
90 minutes	3.0	4.40
120 minutes	2.4	3.61
150 minutes	2.4	3.75
180 minutes	1.8	2.84

Both these sets of results show that there is no incompatibility between an Availability of 0.6 and an Achievement of as much as 90%. They must offer reassurance that such an impressive figure does not simply mean that the aircraft to which it applies can expect to accomplish no more than 60% of its planned sorties.

AVAILABILITY - DEPENDENCE ON RELIABILITY AND MAINTAINABILITY TOGETHER

So far, it has been argued and demonstrated that, for aircraft purposes, measurement of availability must be made against a standard such as a fully successful flying programme if it is to mean anything, and so from here onwards Availability will be measured in terms of degree of achievement of a full day's sorties.

It has been shown also that while achievement increases with increasing Reliability and increasing Maintainability the improvements are not linear and the payoffs are subject to the law of diminishing returns.

The means of illustrating how these three variables, Reliability, Maintainability and Achievement interact with one another is to present the results of the simulation exercises in the form of carpet plots. The following figures are compound plots of the achievements possible from a single aircraft flying a repeated mission of 80 minutes throughout a 12 hour day, with the period for recuperation between successive sorties increasing from 50 minutes (Fig.11), through 80 minutes (Fig.12) to 110 minutes (Fig.13). The Reliability(Maintainability is doubled between one line and the next.

The shapes of the carpet plots shows that while a very reliable aircraft need not be maintainable to the same degree to meet its flying programme, and similarly while a very unreliable aircraft can still meet its missions if it is capable of being rectified very quickly between sorties, and especially if it is given plenty of time between sorties for this to take place, in general, the lines of constant maintainability have a similar slope to those of constant reliability. This means that targets for maintainability must be set and achieved with the same diligence as targets for reliability.

Although reliability, and weapon system reliability in particular, is of prime importance, it is possible that Maintainability has become a poor relation in this particular field of analysis.

The effects of varying maintainability and reliability in the Sea Harrier will be the next subjects to be considered.

HARRIER RELIABILITY

As hinted at earlier in these pages there is no direct relationship between the reliability figures for an aircraft as quoted in source documents such as periodic outputs from the Maintenance Data Centre, and the defect rate it will actually suffer in operational flying conditions. This point is totally lost on many engineering authorities. Therefore, before embarking on Reliability studies for an aircraft type in its operational role, the raw reliability data available must be looked at selectively and only the relevant portions used. Fortunately, informed use of the facilities of the Maintenance Data System makes this possible.

The objective of this exercise is to attempt to forecast the reliability of the Sea Harrier if it were embarked in single or small unit groups. From this reliability the next step is to forecast the Availability of the aircraft in a given role, and thus obtain a set of values by which the worth of the whole enterprise can be assessed.

There is very little Sea Harrier reliability data available as yet, and what there is will be unlikely to be representative of how the aircraft will perform in established service. At this stage of the aircrafts Naval career every malfunction will be cossetted with the attention lavished on a hiccup of a new born babe, and data from a source such as the Intensive Flying Trials Unit is more likely to be misleading than not.

Let us consider instead the Harrier GR III, and allow for the differences between the aircraft later if we need to.

The arising rate for the Harrier GR III for the period 1st January 1978 - 30th June 1978 is 1602 per 1000 flying hours with a defect man-hour rate of 15.5 per 1000 flying hours, (Ref.7). This does not imply however that an aircraft flying one-hour sorties from a ship (or anywhere else for that matter) would suffer an average of 1.6 defects to be rectified after every flight, or that a programme of five sorties a day would generate 75 man hours of rectification work at the end of it. What must be considered is the occasions on which these defects are found. A brief note about the servicing procedures for Military aircraft would be appropriate.

Aircraft Servicing

Aircraft servicing has to be carried out for two main reasons. Either policy directs that something has to be done at set intervals or on certain occasions , or something has been found amiss and needs to be rectified.

Servicing carried out under the first heading is Scheduled Servicing, servicing carried out under the second is Unscheduled Servicing.

Scheduled Servicing embraces all Scheduled activities ranging from Major Servicings carried out at widely spaced time intervals at Maintenance Units at third line, to Flight Servicings carried out repeatedly on the aircraft throughout the flying day. Defects will come to light during any of these activities, but for our current purposes we are interested only in those coming to light during the flying day.

For assessing reliability during a repeated programme of flying, we need to be even more selective, and can afford to discount defects which are revealed during some particular activities of Flight Servicing.

There are three phases of Flight Servicing. First is the Before Flight Inspection (BFI or simply BF). This is carried out before the first flight of the day, and certain servicing actions within it, replenishment of certain reservoirs and tanks for example, may be expected to last the whole flying day through. Then there is the Turn-Round Inspection, TR. As its name implies this is a swift inspection for defects and damage,carried out while the aircraft is being replenished and rearmed. Finally at the end of the flying day comes the After Flight Inspection or AF. This is a very thorough inspection in search of defects which might have accumulated during the day, and which will need to be cleared up,overnight if necessary, before the next BF. Whereas a TR inspection can be carried out in fifteen minutes or less, and should not be on the critical path of the aircraft's replenishment cycle, an AF will take an hour-and-a-half or more.

The aircrew will of course report every defect they have encountered in flight as soon as they come down. Not all these defects need necessarily be rectified before the next flight however.

Selection of Data

While the Maintenance Data System gathers and pools aircraft defect data from all sources and levels of servicing, it is possible to interrogate this pool of information selectively. While searching for representative data to depict the Harriers' reliability in its operational role, the interrogation was limited to a particular batch of Harrier GR III aircraft active in RAF Germany, and limited further to defects arising only from Flight Servicing activities and Aircrew reports. In this way, the defect information collected was expected to bear as close a relationship as possible to what would occur in reality. The breadth of the sample obtained covered a period of approximately 400 flying hours.

Preliminary Analysis

The routine Aircraft Reliability Statistics produced by the Maintenance Data System are presented in a form which has all the aircraft functional systems grouped up into Major Systems; Mechanical, Structural, Propulsion, etc. An example of such a routine output is given at Appendix 5. The aircraft system descriptions themselves correspond in the main to the breakdown used in the Civil Aircraft System designated ATA 100.

The data obtained for this analysis was treated similarly. In addition each arising was scrutinised to see whether or not it could be considered a Grounding Defect, that is, such that it would actually prevent the aircraft from being launched on another mission if it were not rectified. As a guide to making this selection, grounding defects were taken to include all cases of fluid leaks, failures to start, safety equipment deficiencies etc while acceptable defects included cases of engine rpm incorrect, poor communications, and minor structural defects. All problems which might have had an adverse effect on the capability of the aircraft to operate in night or IFR conditions were classified as grounding defects.

The results from this first analysis are shown in Table 13.

Table 13 covers all those defects revealed by the MDC computer interrogation, and so includes all those found in all flight servicing activities. In order to simulate realistic operational conditions, however, flight servicing defects should be confined to those found after one flight and before the next, so defects found by BF and AF servicings could be set aside.

System Group	Arising Rate	Grounding Defect Rate
Mechanical	372	260
Structural	162	18
Propulsion	162	58
Armament	75	20
Tactical Avionics	202	125
Nav + Comms.	68	8
Elect + Instruments	85	18
Photo - Recce	15	0
Totals	1141	507

TABLE 13 - Flight Servicing and Aircrew Defects

Eliminating these defects then leads to the results shown in Table 12.

System Group	Arising Rate	Grounding Defect Rate
Mechanical	225	137
Structural	43	3
Propulsion	95	18
Armament	48	5
Tactical Avionics	133	115
Nav + Comms.	53	8
Elect + Instrument	40	2
Photo - Recce	8	0
Total	645	288

TABLE 14 - Turn-Round and Aircrew Defects

Rates per 1000 Flying Hours.

So starting from an initial overall rate of about 1600 per 1000 flying hours, advised selection of which categories of defects to include and which to exclude brings the rate down to about 1100 (Table 13), 645 (Table 14) and maybe as low as 288 (Table 14).

Thus the value of MTBF to be used in calculations of Availability lies somewhere between 1½ hours and 3½ hours, and although the classification of defects becomes less and less objective as more and more subjective judgements are applied, it is worth taking time to examine the contents of Table 14 more closely in order to determine where the areas of greatest flexibility in defect rates lie, for if these can be identified and hardened up, the true mean time between defect of the in-service aircraft can be edged towards the higher of the two values.

Systems Reliability

Looking within the systems contributing to the system groups, the top four systems repay closer examination. These are listed in Table 15.

System	Arising Rate	Grounding Defect Rate
Fuel System (Airframe)	100	63
Power Plant	83	5
Flt.Nav.Attack	108	105
Communications.	45	8

TABLE 15 (Rates per 1000 flying hours)

Of these key defect areas, the first two, the Airframe Fuel System and the Power Plant, show little difference between their application in the Harrier GR III from which the data is taken, and the Sea Harrier for which it is intended.

a. The Airframe Fuel System

This accounts for nearly one-sixth of the in-use defects and over one-fifth of the grounding defects. Eighty percent of the latter were fuel leaks due to faulty couplings, sleeves and seals found during flight servicing, while an equivalent number of the latter were incorrect indications and warning lamps reported by aircrew during flight phases, surely an unnecessary number of defects for such a well-established system.

b. The Propulsion System

Notable here is the marked disproportion between the rate of defects reported and the number serious enough to ground the aircraft. (T hat the bulk of the defects were not serious is borne out by the absence of any Flight Safety reference in the defect report). Of the 28 defects reported by Aircrew, (70 per 1000 flying hours) 23 were cured by adjustment of the fuel control unit. This leads to one of two deductions.

a. The Fuel Control Unit is unsatisfactory, and so the case for replacing it with a digital unit is given further support.

b. The limits by which the engine is judged are too fine to be realistic. There is no lack of precendent for cases where the RPM limits laid down in the aircrew manual are closer than the tolerances of the actual gauges from which they are read. If this is so the possibility exists that more realistic limits could be set, and a large portion of the defect rate legislated out of existence.

The other two systems, the Nav.Attack System and the Communications System, are not common to the Harrier GR III and the Sea Harrier, but it is not too pessimistic to expect that their reliabilities will turn not to be of the same order.

Maintenance Policy

The data obtained on these 400 flying hours of Harriers GR III can be used to shed some light on which maintenance policy might be the better - to aim to repair by replacement or to aim to rectify all defects in situ. Each policy has its devotees, and maybe one case or the other can be fully supported by the facts.

The defects giving rise to Table 14 are tabulated again in Table 16 , this time listing the Action Taken as on the one hand being an item replacement, and on the other all such actions as Adjust, No Fault Found, Minor Items (e.g.rivets) Replaced, all these actions together making up the heading of Rectified in Situ. Also listed are the rectification man-hours recorded which can be taken as indicating the work content of the job, and hence used as a surrogate for Downtime.

System Group	Rate	Action Taken			
		Replace		Rectify in Situ	
		%	Man Hour Rate	%	Man Hour Rate
Mechanical	225	50	1020	50	630
Structural	43	30	70	70	120
Propulsion	95	27	535	73	434
Armament	48	58	130	42	100
Tactical Avionics	133	73	420	27	115
Nav+Comms	53	80	80	20	15
Elect+Inst.	40	75	230	25	40
Photo Recce	8	70	18	30	16
Total	645	50	2500	50	1470

TABLE 16 - Action Taken and Manhours

Rates for 1000 flying hours

It can be seen that while the Action Taken has been split evenly between the two choices of Replacement and Rectification-in-Situ, repair by replacement costs nearly twice the effort of rectification in situ. It follows that rectification-in-situ must hold a better key to Maintainability.

The Sea Harrier - Reliability

No exercise such as this one had been mounted when the basic requirements for Reliability were stated for the Naval Staff Target, and no work has been carried out to update them. They are set at a round figure of 1000 defects per 1000 flying hours, unqualified by any considerations of what sort of defect is being counted, or at what stage of maintenance it was found. They are, in fact, no more than a rounded-off statement of RAF Harrier reliability current at the time, and the same applies to the requirement for maintainability also.

This simple study has shown that a more realistic value of MTBD can be arrived at with the expense of very little effort, and, along its route, has shown too how vulnerable points of the current aircraft can be identified together with vulnerable areas in its maintenance policy. When the next NSRs come to be written, exercises like this only more thorough should be carried out as a matter of course, for the effort expended will certainly pay dividends when the aircraft is brought into service.

It has been deduced that the in-use Mean Time Between Defects for the Sea Harrier can be expected to be somewhere between 1 and 4 hours, and ensuing Availability work in this paper will use this range of values as its starting point.

The Sea Harrier - Operational Failure Rate

Just as the Reliability requirement in the Naval Staff Target for the Sea Harrier is a direct read-across from the defect rate of the Harrier GR III, so the Operational Failure Rate is a carry-over from that aircraft's own Operational Failure Rate.

While this comparison is at least reasonably satisfactory for overall reliability, it is largely without meaning as far as 'Failure Rate' is concerned.

One of the items of data recorded on the Aircraft MOD Form 720B, which is the input document by which an aircraft arising is reported to the Maintenance Data Centre, is what is known as 'Operational Effect'. This is a parameter recorded by the pilot entering the arising in the Unserviceability Log of the aircraft, and he uses it to state the effect the arising had on his actual sortie. The descriptions at his disposal range from "Accident", through "Mission Failure", "Operational Readiness Broken" and "Engine Shut Down", to "None". A count of the rate at which a positive value of Operational Effect occurs for every 1000 hours' flying can be termed a Failure Rate. This Failure Rate for the Harrier GR III has been rounded off to give a value for the target Failure Rate for the Sea Harrier.

But an arising in an equipment will be detrimental to the success of a flying sortie only if the mission for that sortie was one in which the equipment was going to be used. So a malfunction can be classed as a Failure in some sorties, and only as an Arising in others. So the 'Failure Rate' calculated at the end of a recording period will be as much dependent on the mixture of mission types during that period as it will on the reliability (or rather unreliability) of the aircraft's systems.

There is no point therefore in quoting the experienced Failure Rate for one aircraft type fitted with one particular set of systems and exercised in one particular family of roles as a target requirement for another aircraft fitted with different systems and exercised in another family of roles. It means nothing to the operator who sets the target and cannot mean anything either to the manufacturer who undertakes to meet it.

This is not to say that an Operational Failure Rate target value should not, or cannot be specified. The set value is usually stated as a success probability for a mission of given length, and the appropriate failure rate is calculated from that. For example a target of 95% reliability for a sortie of 2 hours leads to a required Mean Time Between Failure value equal to 39 hours, calculated as

$$\underline{\mathrm{Exp}(-2/39) \quad = \quad 0.95}$$

This is all very well as far as it goes, but it does not go far enough. The reason is that it extends only to the aircraft and not to the weapon the aircraft discharges - which is the whole point of the mission. The Reliability of the aircraft should start to be quantified at the Staff Target stage, and the Mission Reliability should include the probability of scoring a hit. This means that the weapon system reliability of the aircraft may have to be very nearly 100% and its Mean Time Between Defects will be very high as a result, but any other definition than this, while reassuring, will be largely meaningless.

Weapon effectiveness is, for the time being at any rate, outside the scope of this paper. For the present we will continue to consider the subject of reliability only insofar as the probability with which it interferes with the capability of the aircraft to fly its next sortie.

FORECASTING SEA HARRIER AVAILABILITY

In the absence of any definition that is capable of being put to work, Availability has been locally defined in this paper as being the measure of the probability that the aircraft will fulfill the flying programme set for it.

In this definition, Availability has been shown to be dependent equally on Reliability, measured as Mean Time Between Defects, Maintainability, measured as Mean Time to Repair, and the parameters of the Flying Programme itself especially the recovery period between one sortie and the next.

Simple programs have been devised to illustrate this interdependence, and to highlight that Maintainability can be just as important a feature of the aircraft as is Reliability.

Availability of a single aircraft

The examples used so far have been based on the somewhat unreal scenario of a single aircraft attempting to fly a programme. This degree of unreality notwithstanding, it is nevertheless reasonable to study the carpet plots in Figures 11, 12 and 13 and draw the inference that an aircraft with an MTBF of about two hours and an MTTR of about four hours can meet about 70% - 80% of a continuous flying programme in a day. In other words it should be possible to get an average of 4 x 80 minute sorties out of one Sea Harrier in a flying day. This particular aspect of the study has not been pursued any further at this stage, but could be taken up again very easily.

Availability of two or more aircraft

Of more realistic value is the question of what cover, or what proportion of the time, could be given by two or more aircraft attempting to meet a set flying pattern.

The flying programme chosen for this exercise is a "one-over-one" Combat Air Patrol in which one aircraft is always on station, each one returning to land only when relieved by its successor. A CAP time of 75 minutes is used, initially, with an overlap of 15 minutes, so that the number of sorties launched should equal the number of hours in the flying day.

The subject for investigation is the question of how well such a CAP could be sustained from a pool of 2, 3 or 4 aircraft. It is worth noting that it makes no difference to the result whether all aircraft operate from the same ship or whether each operates as available from a single-unit ship. The probabilities and requirements remain the same.

The Program

The program used in this investigation is a development of the single-aircraft program used previously, adapted to cope with up to four aircraft and making the same simplifying assumptions i.e. all aircraft are returned to a serviceable condition overnight, no queuing problems arise for servicing, work is started immediately on landing etc.

The program, SCAU, together with its basic flow chart is shown at Appendix 6.

It is run for a notional 100 days and the form of the output is to tabulate on how many of these days a given number of sorties was achieved, so that the results could be read as a histogram.

Results - 2 Aircraft

A copy of the results obtained from running the program with two aircraft over a flying day of 10 hours, (i.e. maximum sorties = 10), is overleaf. For this output, both MTBF and MTTR went up in linear steps of 30 minutes apiece.

As may be seen from the final set, the probability of achieving all 10 sorties is only 66% with the MTBF at its extreme value of 4 hours and an MTTR value of an extremely optimistic 30 minutes. It being accepted that full serviceability from two aircraft is too much to ask, a more reasonable goal is to set a target of at least eight out of the ten sorties. The probability of achieving this are the sums of the figures in the first three columns of results, and are plotted in Figure 14(1)

Discussion

The extreme sensitivity of the probability of achieving the required eight sorties to small variation in both MTBF and MTTR is immediately apparent, but it can be done with at least 85% confidence if the MTBF is at its best predicted, i.e. most tolerant, value of 4 hours.

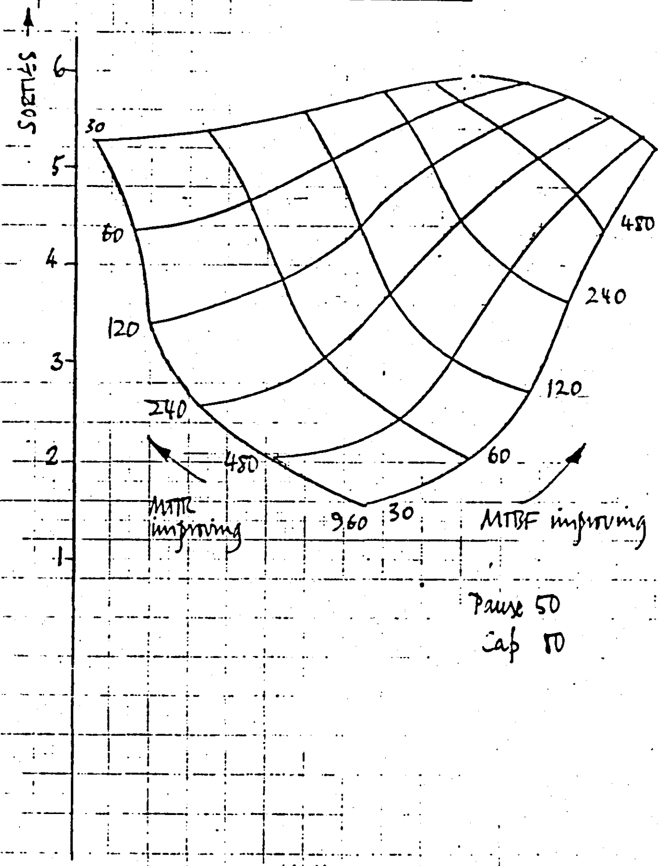
In order to illustrate the relationship between MTBF and MTTR more clearly it is necessary to introduce a further step of probability into the discussion. Let us declare that we want at least an 80% chance of achieving at least eight sorties out of ten. By plotting the values of MTTR and MTBF where they are intersected by a cross-section taken at the 80% level, we can produce the curve shown in Figure 15.

This curve shows that if the existing values of MTBF and MTTR put the working point to the left of the line then this particular flying programme can be achieved with a probability of 80% or more, and if they put it to the right, then the probability is less.

As MTBF (i.e. Reliability) increases the line curves over to the right. The reason for this is that the simulated value of MTBF eventually reaches a value high enough for the required results to be achieved without an unserviceable aircraft ever needing to be rectified at all. From this point on, the results will be independent of MTTR altogether.

While looking at Figure 15, and those which follow, it is as well to bear in mind that the values of the reliability parameters which the Sea Harrier is expected to return are an MTBF of between 60 and 240 minutes and an MTTR of about 240 minutes, that the results of the simulation are very sensitive to the prevailing values of these parameters and that these values themselves are the mean values of a very broad spectrum. On the bright side this

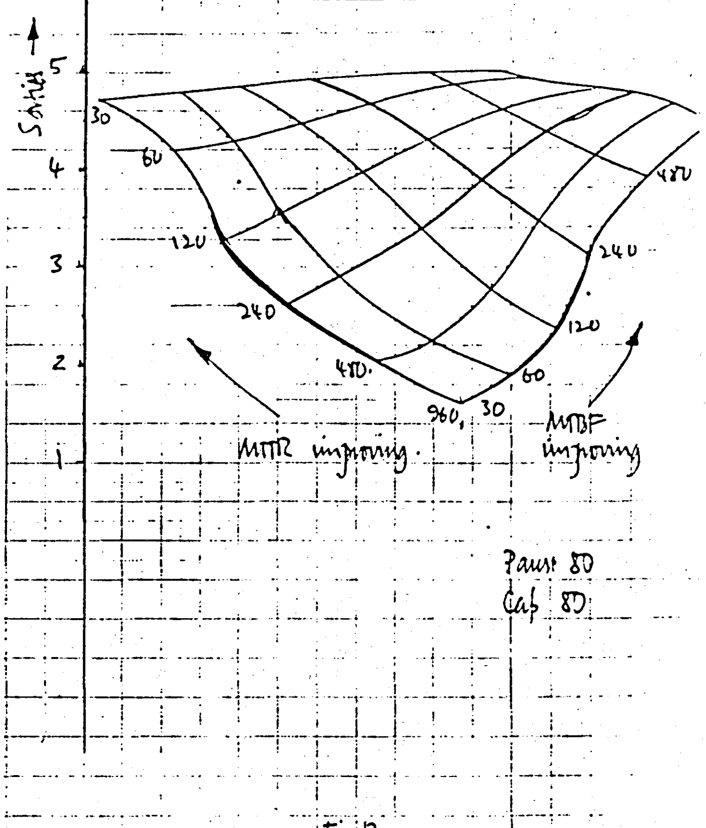
RELATIONSHIP BETWEEN SORTIE RATE MTTR AND MTBF



Pause 50
Cap 80

— Fig 11 —

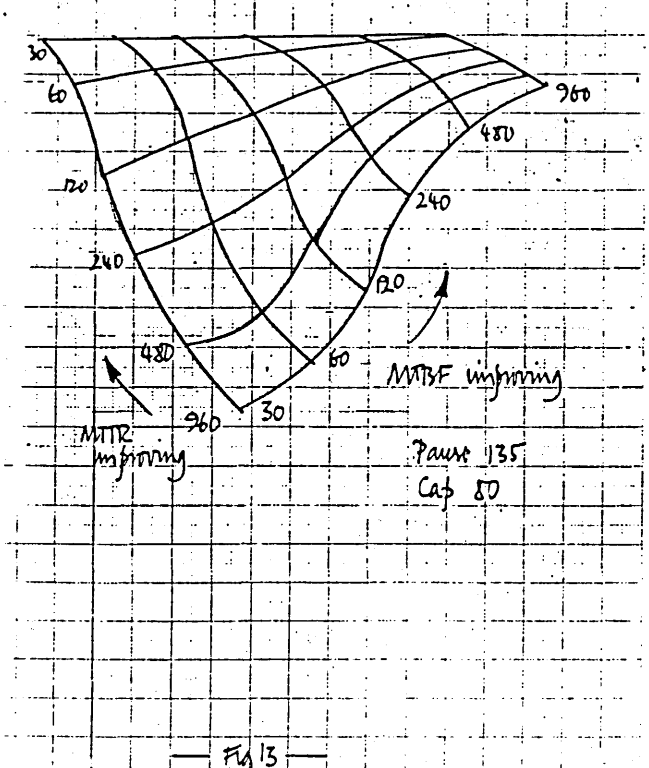
RELATIONSHIP BETWEEN SORTIE RATE, MTTR + MTBF



Pause 80
Cap 80

— Fig 12 —

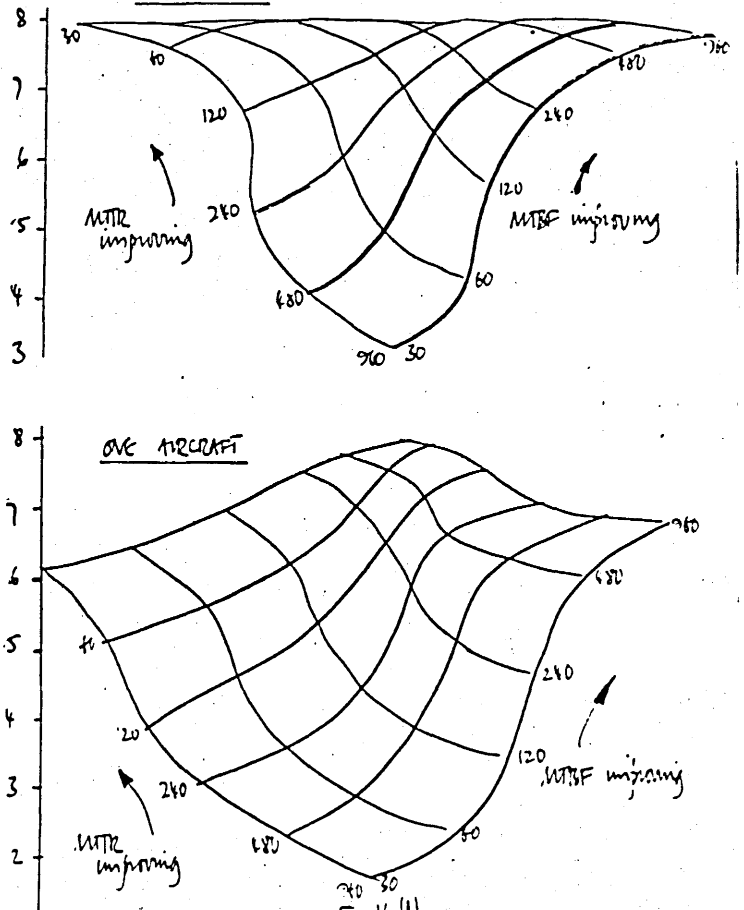
RELATIONSHIP BETWEEN SORTIE RATE, MTTR + MTBF



Pause 135
Cap 80

— Fig 13 —

RELATIONSHIP BETWEEN SORTIE RATE MTTR + MTBF



— Fig 14 (1) —

AVAILABILITY ON COMBAT AIR PATROL

Pool = 2

MTBF	MTTR	CAP	X	IX	VIII	VII	VI	V	IV
30.	30.	75	14.	80.	6.	0.	0.	0.	0.
30.	60.	75	0.	69.	27.	4.	0.	0.	0.
30.	90.	75	0.	29.	53.	17.	1.	0.	0.
30.	120.	75	0.	15.	54.	28.	2.	1.	0.
30.	150.	75	0.	9.	35.	43.	11.	2.	0.
30.	180.	75	0.	7.	26.	46.	12.	9.	0.
30.	210.	75	0.	4.	22.	41.	17.	11.	5.
30.	240.	75	0.	2.	19.	35.	23.	11.	9.
30.	270.	75	0.	0.	20.	27.	30.	9.	12.
30.	300.	75	0.	0.	17.	25.	28.	15.	10.
30.	330.	75	0.	0.	13.	25.	27.	17.	12.
30.	360.	75	0.	0.	8.	26.	26.	22.	9.
60.	30.	75	26.	70.	4.	0.	0.	0.	0.
60.	60.	75	0.	77.	21.	2.	0.	0.	0.
60.	90.	75	0.	46.	45.	8.	1.	0.	0.
60.	120.	75	0.	28.	53.	17.	2.	0.	0.
60.	150.	75	0.	16.	52.	26.	6.	0.	0.
60.	180.	75	0.	13.	46.	27.	11.	3.	0.
60.	210.	75	0.	10.	40.	31.	12.	5.	2.
60.	240.	75	0.	9.	31.	37.	13.	8.	2.
60.	270.	75	0.	6.	27.	39.	15.	10.	2.
60.	300.	75	0.	5.	23.	40.	18.	9.	3.
60.	330.	75	0.	4.	20.	38.	21.	11.	4.
60.	360.	75	0.	4.	14.	42.	21.	12.	5.
90.	30.	75	34.	64.	2.	0.	0.	0.	0.
90.	60.	75	6.	73.	19.	2.	0.	0.	0.
90.	90.	75	3.	55.	38.	4.	0.	0.	0.
90.	120.	75	1.	40.	48.	11.	0.	0.	0.
90.	150.	75	1.	28.	49.	21.	1.	0.	0.
90.	180.	75	1.	25.	44.	27.	3.	0.	0.
90.	210.	75	1.	19.	43.	28.	9.	0.	0.
90.	240.	75	1.	15.	41.	31.	7.	5.	0.
90.	270.	75	1.	13.	40.	29.	11.	6.	0.
90.	300.	75	1.	12.	33.	36.	12.	6.	0.
90.	330.	75	1.	12.	31.	35.	12.	8.	1.
90.	360.	75	1.	11.	27.	37.	15.	8.	1.
120.	30.	75	41.	57.	2.	0.	0.	0.	0.
120.	60.	75	11.	75.	14.	0.	0.	0.	0.
120.	90.	75	5.	65.	27.	3.	0.	0.	0.
120.	120.	75	2.	54.	39.	5.	0.	0.	0.
120.	150.	75	1.	41.	47.	11.	0.	0.	0.
120.	180.	75	1.	36.	46.	16.	1.	0.	0.
120.	210.	75	0.	30.	49.	16.	5.	0.	0.
120.	240.	75	0.	28.	42.	24.	5.	1.	0.
120.	270.	75	0.	28.	39.	27.	5.	1.	0.
120.	300.	75	0.	24.	40.	26.	9.	1.	0.
120.	330.	75	0.	23.	40.	25.	10.	2.	0.
120.	360.	75	0.	22.	37.	26.	12.	3.	0.
150.	30.	75	54.	45.	1.	0.	0.	0.	0.
150.	60.	75	18.	73.	8.	1.	0.	0.	0.
150.	90.	75	13.	62.	23.	2.	0.	0.	0.
150.	120.	75	6.	55.	37.	2.	0.	0.	0.
150.	150.	75	5.	48.	41.	5.	1.	0.	0.
150.	180.	75	5.	43.	42.	8.	1.	1.	0.
150.	210.	75	4.	39.	43.	12.	1.	1.	0.
150.	240.	75	4.	34.	44.	15.	2.	1.	0.
150.	270.	75	3.	34.	40.	20.	2.	1.	0.
150.	300.	75	3.	31.	41.	22.	2.	1.	0.
150.	330.	75	3.	31.	39.	23.	3.	1.	0.
150.	360.	75	3.	28.	40.	25.	3.	1.	0.

```
180.   30.   75. 52. 46.  2.  0.  0.  0.  0.
180.   60.   75. 22. 67. 11.  0.  0.  0.  0.
180.   90.   75. 14. 67. 17.  2.  0.  0.  0.
180.  120.   75. 10. 63. 23.  4.  0.  0.  0.
180.  150.   75.  9. 54. 30.  6.  1.  0.  0.
180.  180.   75.  9. 43. 33.  8.  2.  0.  0.
180.  210.   75.  8. 41. 38. 11.  2.  0.  0.
180.  240.   75.  6. 39. 40. 12.  3.  0.  0.
180.  270.   75.  4. 39. 40. 13.  4.  0.  0.
180.  300.   75.  4. 34. 44. 14.  4.  0.  0.
180.  330.   75.  4. 29. 47. 15.  5.  0.  0.
180.  360.   75.  4. 26. 49. 15.  6.  0.  0.
210.   30.   75. 59. 41.  0.  0.  0.  0.  0.
210.   60.   75. 31. 58. 11.  0.  0.  0.  0.
210.   90.   75. 20. 60. 18.  2.  0.  0.  0.
210.  120.   75. 18. 51. 27.  4.  0.  0.  0.
210.  150.   75. 17. 47. 30.  6.  0.  0.  0.
210.  180.   75. 14. 45. 32.  8.  1.  0.  0.
210.  210.   75. 13. 41. 35. 10.  1.  0.  0.
210.  240.   75. 13. 33. 35. 13.  1.  0.  0.
210.  270.   75. 11. 38. 34. 16.  1.  0.  0.
210.  300.   75.  9. 37. 37. 15.  2.  0.  0.
210.  330.   75.  9. 37. 33. 19.  2.  0.  0.
210.  360.   75.  9. 32. 35. 22.  2.  0.  0.
240.   30.   75. 65. 34.  0.  0.  0.  0.  0.
240.   60.   75. 35. 60.  5.  0.  0.  0.  0.
240.   90.   75. 25. 61. 13.  1.  0.  0.  0.
240.  120.   75. 20. 55. 24.  1.  0.  0.  0.
240.  150.   75. 13. 49. 29.  4.  0.  0.  0.
240.  180.   75. 16. 49. 27.  7.  1.  0.  0.
240.  210.   75. 14. 47. 28. 10.  1.  0.  0.
240.  240.   75. 14. 46. 28. 11.  1.  0.  0.
240.  270.   75. 12. 45. 29. 13.  1.  0.  0.
240.  300.   75. 12. 41. 33. 12.  2.  0.  0.
240.  330.   75. 11. 41. 34. 12.  2.  0.  0.
240.  360.   75. 11. 41. 33. 13.  2.  0.  0.

**** END OF STREAM  CA536S   :   113
```

means that even the most optimistic predictions have a good chance of being realised.

Results - Two Aircraft or More

Given a simulation program capable of playing tunes not only on the fundamental input of MTBF and MTTR, but also all the other variables like sortie length, overlap period and length of the flying day, the temptation is very great to carry out a thorough and exhaustive exploration of the whole range of interactions capable of being exercised.

For a start, however, exploration has been restricted to just one type of flying programme, that of flying a sortie of 75 minutes duration with a 15 minute overlap between launch of one aircraft and recovery of the next, the length of the flying day being 12 hours, thus aiming for a maximum possible achievement of twelve sorties. This is thought to be representative of the sort of task likely to be set a ship carrying and operating two aircraft or more.

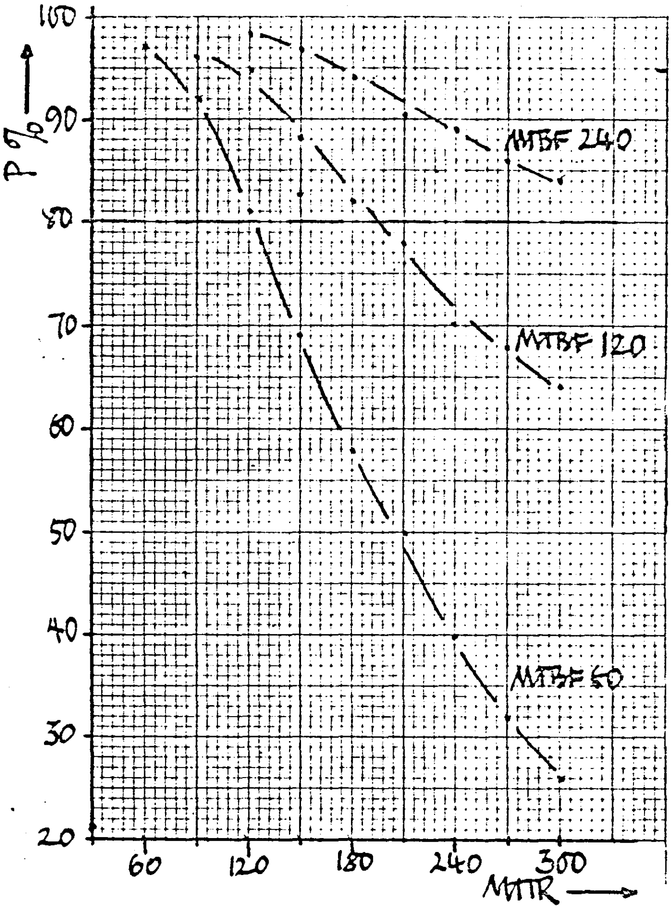
How many aircraft?

Consider Figures 16, 17 and 18. These depict the probabilities of achieving at least eleven out of the twelve sorties planned, given a holding of two, three and four aircraft, and a value of Mean Time Between Failure of 60, 120 and 180 minutes respectively.

Over this representative range of reliability values it is clear that two aircraft are never enough to meet the task, while four aircraft are usually more than enough given an MTBF of 120 minutes, the expected lower limit of the in-use value.

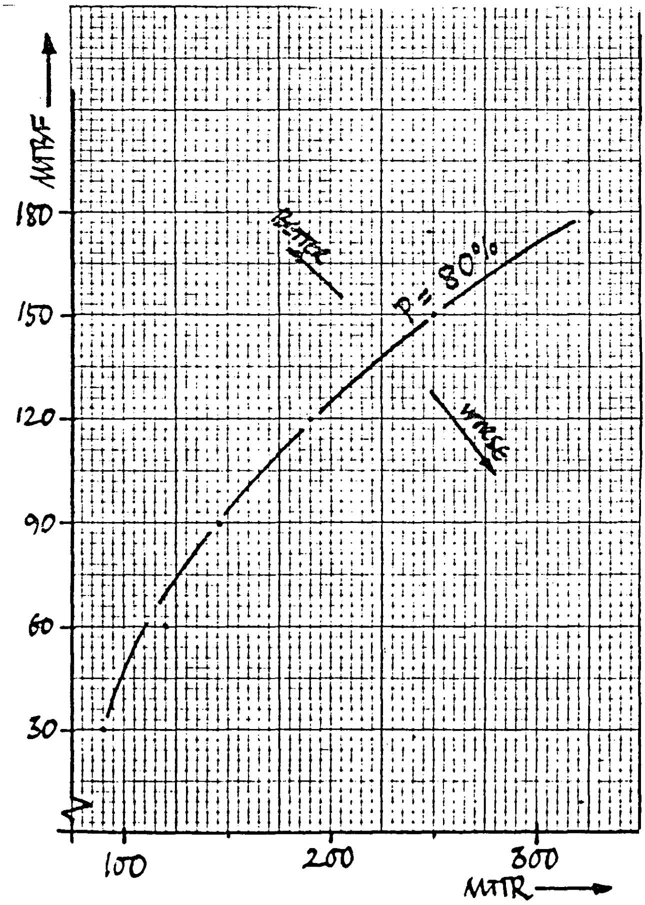
It can be deduced also that a major effort into reducing the Mean Times to Repair would be repaid handsomely in terms of aircraft savings even if reliability were to stay the same. In Figure 17 for instance it is clearly demonstrated that two aircraft could do the work of three if only the repair time could be reduced from 170 minutes to 70 minutes. As far as the writer is aware, this basically elementary analytical approach to the problem has still to be used when the respective merits of rival policies for aircraft maintenance and support are being compared.

The conclusion to be drawn from Figures 16, 17 and 18 is that given reliability and maintainability values in the range we are considering to be applicable to the Sea Harrier the minimum number of aircraft to embark in order to have a good chance of maintaining one aircraft on a CAP sortie



— Fig 14(2) —

Two Aircraft Operation.
Probability of 8 sorties
minimum out of 10.
Sortie length = 75 min



— Fig 15 —

Two Aircraft Operation.
MTTR/MTBF relationship
to achieve 8 sorties out of 10.
Sortie length = 75 min

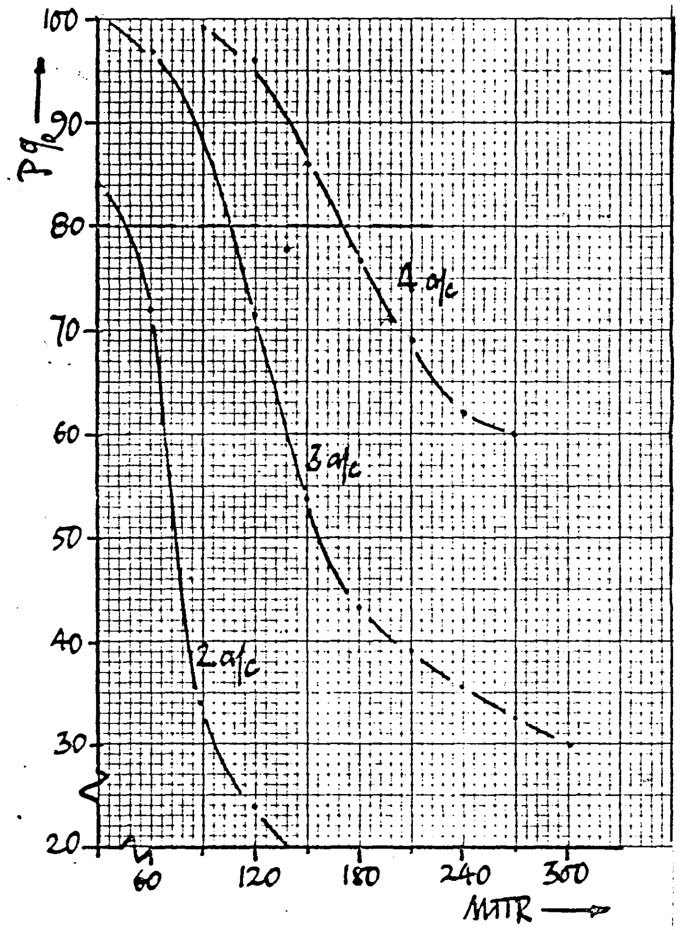


Fig 16

Multi-Aircraft Operation.
Probability of achieving at leas
11 sorties out of 12.
MTBF = 60
Sortie length = 75

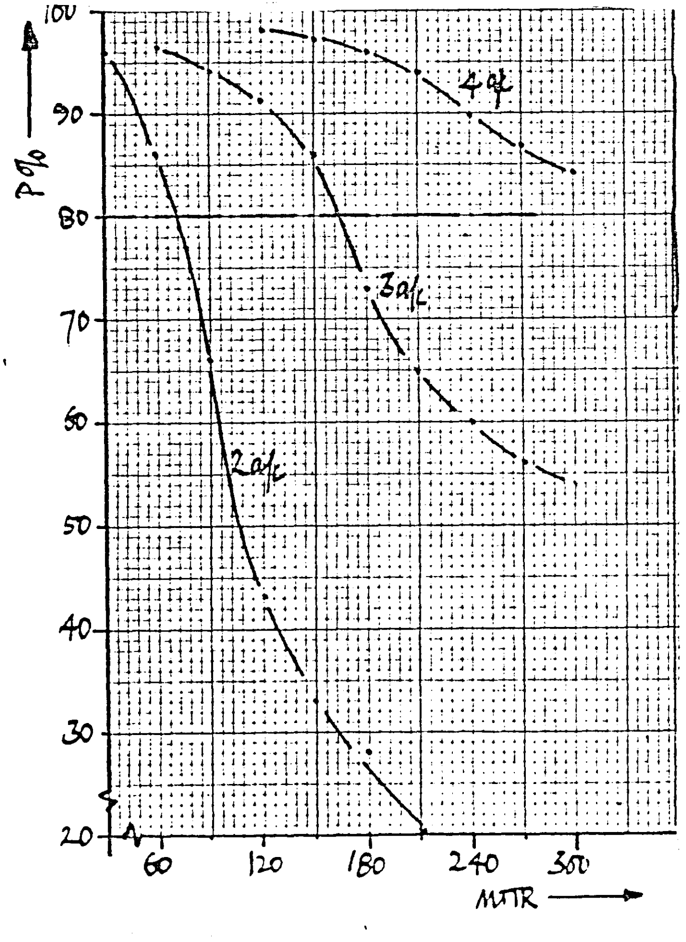


Fig 17

Multi-Aircraft Operation.
Probability of achieving at least
11 sorties out of 12.
MTBF = 120
Sortie length = 75

of 75 minutes for eleven hours out of twelve would be three.

Curves for an AE of three are drawn in Figure 19 and cross-sections (corresponding to Figure 15 for two aircraft) are plotted in Figure 20. With the Reliability value at its most tolerant, i.e. an MTBF of 240 minutes, and the Maintainability value even where it is now, i.e an MTTR of 240 minutes also, then the success probability can be seen to be 90% or greater.

Short Sorties

These predictions may appear to be rather modest when compared with the rates of striking claimed by other operators. As mentioned previously, the USMC have rattled off over 40 sorties from 6 aircraft in just over 2 hours, while the RAF claims to be able to fly up to 10 sorties a day for its Harriers in the field (Ref.8).

Part of the secret of their success lies in the brevity of the sorties flown, only 14 or 20 minutes in the case of the US Marines. The claims of the RAF, too, are qualified by the admission that only 20% of the missions flown during a representative exercise involved weapon delivery on a range. The implication is then that the weapon system was not fully exercised during 80% of these sorties, and in consequence, the defect rate was appropriately reduced.

The implications of flying short sorties are shown in Figure 21. This uses the same shape of flying programme as that used to produce Figures 16, 17 and 18, but the sortie length is less (35 minutes compared with 75) and so is the flying day. For three aircraft it can be seen that an MTBF of slightly better than two hours is good enough to make the results effectively independent of MTTR.

Figure 22 shows the same programs run this time for a holding of just two aircraft. It shows that with reliability adequately, (but not unrealistically), high, they are enough to keep the programme going at a probability level of 80%.

A final run in the series was made with a set task of at least 14 sorties out of 15 for the same length of sortie. Given Reliability and Maintainability values of MTBF = 180 minutes and MTTR = 120 minutes respectively, it was shown that the probability of achieving at least 14 sorties out of 15 from an AE of two aircraft was 64%, while with the sights set somewhat lower, with a target of at least 13 sorties out of 15, the probability rose to 93%. This is, in effect, the probability of getting about seven

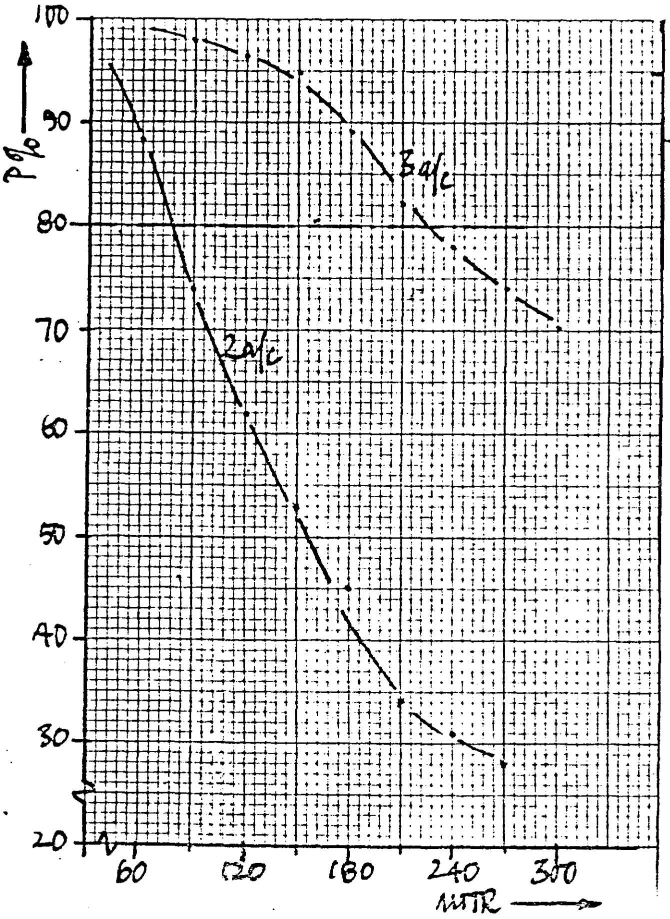


Fig 18

Multi Aircraft Operation.
Probability of achieving at leas
11 sorties out of 12.
MTBF = 180
Sortie length = 75

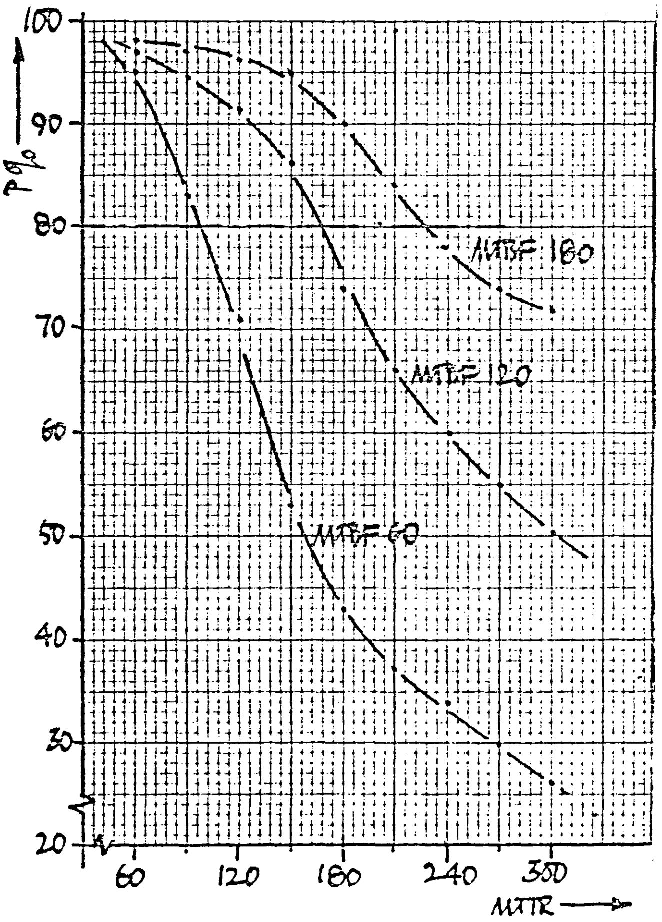


Fig 19

Three Aircraft Operation.
Probability of achieving at least
11 sorties out of 12.
Sortie length = 75

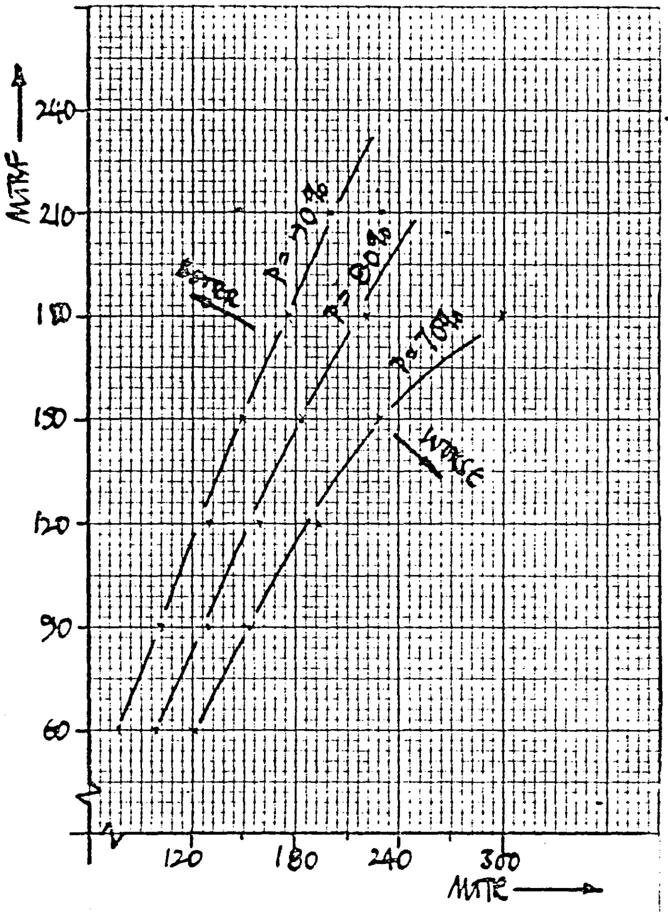


Fig 20

Three Aircraft Operation.
MTTR/MTBF relationship
to achieve 11 sorties out of 1
Sortie length = 75

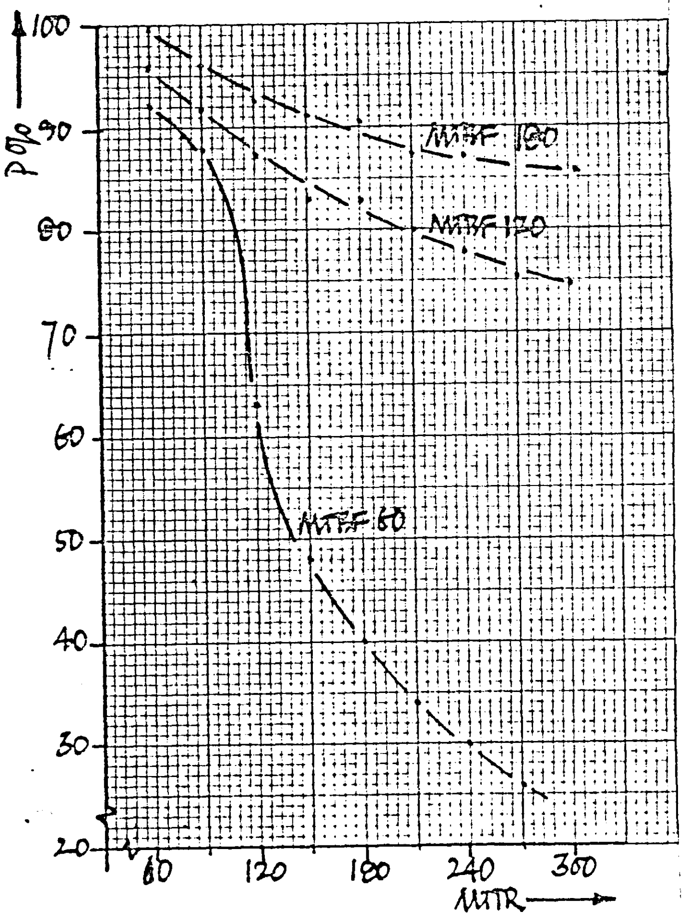


Fig 21

Three Aircraft Operation.
Probability of at least
11 sorties out of 12.
Sortie length = 35

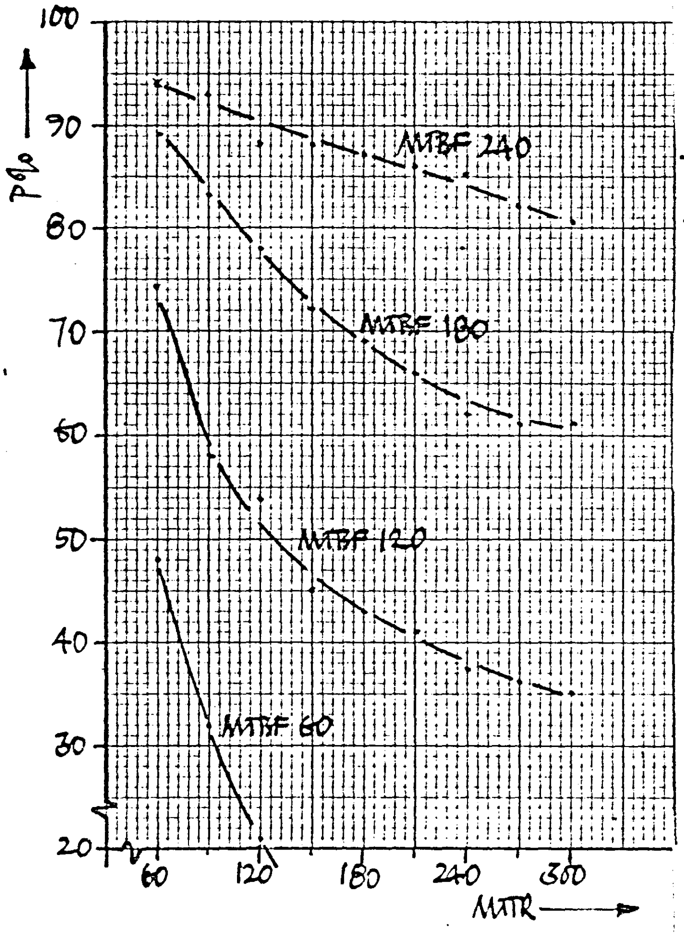


Fig 22

Two Aircraft Operation.
Probability of at least
11 sorties out of 12.
Sortie length = 35

sorties of over half an hour out of each of two aircraft.

The RAF flying rates of eight or ten sorties per aircraft per day can be matched, then, by the hypothetical aircraft used in these simulations. This demonstration has a useful and encouraging corollary. If such a striking rate can be achieved in theory given that the MTBF is as high as 180 minutes or more and the MTTR is 240 minutes or less, and if it is demonstrable, as well, in practice, then reliability and maintainability values such as these can be achieved in practice, and so more elaborate performance predictions based upon them have a very good chance of coming true.

CONCLUSIONS

1. Availability Definitions

It is not as easy to produce a definition of Availability that will hold water as some authorities would choose to think. While a high value of Availability as usually defined does indicate better use of aircraft than does a low one, the relationship is neither straightforward nor does it depend exclusively on MTBF and MTTR. It depends on the flying programme as well, if its interpretation is to be more than just superficial.

This understood, Availability can be defined in terms of the probability of realising a given task over a given period, and is best quantified by simulation methods. If these are impracticable, then a good substitute is Operational Readiness as defined in Ref.3.

2. Sea Harrier Availability Parameters

a. Reliability

The definition of this measure too must be governed by the use to which the results are intended to be put, for it to be of the greatest use.

If Reliability is to include all arisings encountered from all sources, then the value for the Sea Harrier will be of the same order as that for the Harrier GR III, i.e. an MTBF of about 40 minutes. The defect rate experienced in daily use will be such as to raise this figure to 120 minutes, and for short periods, such as during intensive flying, this can increase to about 240 minutes. It is unlikely to exceed this value.

b. Maintainability

(i) The base figure for Maintainability as taken from the data furnished to the MOVES model is 3.91 hours. Operationally this can be reduced to two hours or less.

(ii) For future aircraft, this reduction could be best achieved by designing exclusively for rectification-in-situ. A preliminary survey of maintenance data derived from Harrier GR III experience shows that the alternative, repair-by-replacement, is twice as costly in man-hours.

c. Availability

Given the values of MTBF and MTTR discussed so far, the Availability for the types of sortie considered will be as in Figures 14 - 22.

3. Sea Harrier Deployment

a. Single Aircraft

An aircraft on individual detachment to a ship could fly four or even five sorties of 80 minutes duration during a twelve-hour day. For short flights it should be able to match its RAF opposite number and achieve eight sorties or more, for short periods at least. This sort of task is not in keeping with the job for which the aircraft has been procured, but could arise if it were embarked for close air support, i.e. if an amphibious role were found for it, or, (more likely) in demonstration flying.

b. Multi Aircraft

A twelve-hour Combat Air Patrol flying one-over-one can be sustained with a high degree of success by three aircraft. This is asking for an average of four sorties per aircraft per day, which is what is expected of a singleton. Two aircraft would be overstretched and four aircraft would be more than enough.

4. Support

With so many variables to hand, it is not possible to bring about a perfect optimisation of an activity like aircraft operations at sea. What can be done however, is to identify the parameter most likely to bring about success or failure, get it under control, and follow it in the direction that proves to be the most rewarding.

In this case that parameter appears to be the measure of Maintainability. While the elementary simulation technique employed has assumed a negative exponential distribution of MTTR to obtain, it seems unlikely that any other distribution deemed appropriate, log-normal, deterministic, or whatever, would have led to any conclusions other than that aimed at. That is that within the range of aircraft reliability expected from the Sea Harrier, the success probability of the flying programme is profoundly dependent on the MTTR, and for this probability to be high enough, the MTTR must never rise above a limit of about four hours. Furthermore, the rewards for halving it are great indeed.

Achievement of this goal is the next problem.

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APPENDIX 1

CONTROL OF AVAILABILITY

In the past, Command has sought to use figures of Availability returned by its subject squadrons as a means of assessing the effects of

a. Impact of modification

b. Variation in logistic support

c. Quality of squadron management

(Ref.10)

This is not directly possible. The reason is that all sorts of variations in the elements listed could occur collectively without the end result being changed at all, and thus without being detected it is used as a monitor.

Availability depends on three factors:

a. The flying program

b. The defect rate

c. The rate of recovery from defects

All three of these could be varied in such a way as to leave Availability unaltered. For a set flying task, one excellent squadron mana-ement coping with a high defect rate could produce the same Availability as a worse squadron management coping with a lesser, and the difference in quality would never show.

Data in the availability field does exist however, for the effect of variables to be monitored. The point is that the Availability value alone does not convey sufficient information for this purpose.

Effect of Modification on Availability

If a defect rate is reduced as a result of Modification action, the potential effect of a Modification can, and indeed should , be determined before it is approved and fitted. We have control of Modifications and can watch Availability to see whether they work; it is not sufficient to watch the Availability and try to attribute changes to the results of Modifications.

Effects of Logistic Support and Squadron Management

Poor performance in logistic support and squadron management will both show in the form of defects taking a long time to be rectified and thus in an adverse effect on Availability. This might be masked however, if it coincided with a period of less-than-normal defect rate. If the objective of monitoring Availability is not just to recognise the symptoms but also to cure the disease then the data to examine is the raw data of recovery times. Experience is that 90% of all defects are rectified within a relatively short time (Ref.1), and that it is the long term defects that have the most disruptive effect on Availability in practice. These can be identified at the expense of very little effort, given a data retrieval system like that offered by the Maintenance Data System, and it is then up to the Command or any other higher formation to investigate whether the job took so long because of logistic problems, squadron difficulties or any interactive variation of the two.

APPENDIX 2

GENERATION OF PSEUDO-RANDOM NUMBERS (Ref.9)

One method of generating random numbers on a Digital Computer is to prepare and store a set of random numbers in tabular form, either in the core of the machine or in a peripheral. While this approach may be essential for major simulation tasks, a far simpler one will suffice for the task in hand in this paper, and the method used is to generate not random numbers but pseudo-random numbers.

Paradoxically, the most commonly used generator of random numbers is an algorithm which produces a non-random sequence of numbers, each of which is completely determined by its predecessor, and consequently all of which are dependent on the value of the initial number. If the constants in the generator are chosen with appropriate care, the numbers produced will be sufficiently independent of one another for most practical purposes. Because such numbers can be used to fulfil the task of random numbers, but are not themselves inherently random, they are termed 'pseudo-random' numbers.

The generator has the form:

$$Z_i \equiv aZ_{i-1} + c \pmod{m} \quad i=1,, n,$$

which can be taken to mean 'the remainder when as many whole multiples of m have been subtracted'.

As Z_i is always less than m, it follows that the number of pseudo-random numbers generated can not be more than m, and the nature of the generator is such that once any individual number comes round again, the whole sequence will be recycled. The value of m must be chosen such that as many distinct numbers are generated as are required, and the values of a, Z_o and c used to be chosen in such a way that as many of the m numbers as possible recur in the cycle. If P is the total number of numbers that can occur out of the m possible ones, the generator is said to have full period when $P = m$

For full period to be achieved the following conditions must be fulfilled:

i. The value of c must be relatively prime to m, that is, they must have no factors in common other than unity.

ii. For every prime factor q of m, $a \equiv 1 \pmod{q}$, that is $a = 1 + qK$.

iii. If 4 is a factor of m, $a \equiv 1 \pmod{4}$.

For the simulation carried out in this paper, values to generate the two ranges of random numbers required were chosen as follows:

i. m = 100, thus there may be up to 100 numbers generated

ii. The prime factors of 100 being 2 and 5, (and 4 being a factor as well), values of a were chosen from the range 21, 41, 61, etc.

iii. As c can take any value not divisible by 2 or 5 it was set at 7 and 17.

iv. Z_o was set at 50 in each case.

A representative sequence of pseudo-random numbers may be demonstrated as a programmable calculator (TI 57) using the input program below:-

LRN, RCL1 x RCL2 + RCL3 = STO 0

RCL0 ÷ RCL4 = STO 5

RCL5.2nd Int x RCL4 - RCL0 = 2nd/x/2nd Pause STO 1

RST.LRN

Z = STO1 = 50

a = STO2 = 21, 41, 61 etc

c = STO3 = 7 or 17

m = STO4 = 100

APPENDIX 3

HARRIER MISSION TIMES FOR AVAILABILITY ESTIMATIONS

Operating data for this Appendix are taken from the Operating Data Manual (ODM) for the Harrier GR 3 (Ref.4) at takeoff weights of 19500 lb (without drop tanks) and 21,700 lb (with drop tanks). They are assumed to be valid for the Sea Harrier FGR 1.

BASIC DATA:-

	lb
Empty weight	12,500
Pilot+LOX+water+oil	500
Operating weight	13,000

FUEL AND ARMAMENT

Full internal fuel
Gun pod plus 130 rounds
Sidewinder missile on outboard pylon
(Assume: Practice Bomb Carrier + 70lb)

Then Mission A:- Empty inboard pylon

Mission B:- Inboard full drop tanks

WEIGHT AND DRAG INDEX

	A		B	
Gunpods	926	2½	926	2½
Sidewinders Droptanks	450	1	2250	7½
Centerline Pylon	52	½	52	½
	1428	4	3228	10½

	A	B
Internal Fuel	5060	5060
Takeoff Weight	19500	21700
Fuel at startup	5060	6660
Useable fuel (assuming 5% reserve)	4800	6270
Fuel for takeoff, acceleration, approacy, overshoot, 1 landing (ODM Sect.11)	1000	1000
Useable fuel for flight	3800	5270
<u>CLIMB</u> (ODM Sect.4)		
Assuming 500 lb already used;		
Climb to 25000 ft		
Time	3 min	3.7 min
Distance	23 mi	37 mi
Fuel	400 lb	550 lb
<u>DESCENT</u> (ODM Sect.6)		
Time	2 min	2 min
Distance	19 mi	20 mi
Fuel	60 lb	55 lb
∴ Fuel available for CAP	2840	4165

Assume aircraft on CAP station will loiter at maximum endurance speed while awaiting an assignment

From ODM (Section 5.3) this is 250 knots IAS (0.63 M)

	A	B
Mean Cruise Weights	18000	20000
From Fig.5.7 and 5.8 resp.		
WV/Q ÷ 18000	15.5	15.0
Specific Air Range	15.5	13.5
From Fig.5.1, TAS	390	390
From Fig.5.4, fuel flow	42	49
Assume 5 mins combat at 150 lb/min	750	750
Fuel remaining	2090	3415
Endurance at 0.63M	50 mins	69 mins
Flight times break-down:-		
Takeoff, land	2	2
Climb, flight, descend	10	11
Loiter	50	69
Total Sortie	62	82

APPENDIX 4

PROGRAM SCAR.

```
                LIST SCAR
            MASTER PROG
C           AVAILABILITY ON COMBAT AIR PATROL
C           MAIN CALCULATION
            REAL MTBF, MTTR,MEND
            WRITE(2,98)
            WRITE(2,100)
            MTBF=60
40          MTTR=240
30          CAP=60
20          DAY=720
19          RAND=50
            RANE=50
            PAUSE=30
21          A=1
            D=0
            E=0
4            TIME=0
            MEND=0
            FLTS=0
5           TIME=TIME+CAP
            FLTS=FLTS+1
            B=EXP(-CAP/MTBF)
            RAND=AMOD(21.*RAND+7,100.)
            IF((RAND/100).GE.B)GO TO 10
6           TIME=TIME+PAUSE
7           IF(TIME.LT.DAY)GO TO 5
            GO TO 15
10          RANE=AMOD(41.*RANE+17,100.)
            C=-MTTR*ALOG(1-RANE/100)
            IF(C.LE.(DAY-TIME))GO TO 8
            C=DAY-TIME
8           MEND=MEND+C
            IF(C.LE.PAUSE)GO TO 6
            Z=(C-PAUSE)/(CAP+PAUSE)
            NZ=IFIX(Z)
            Z=FLOAT(NZ)
            TIME =TIME+(Z+1.)*(CAP+PAUSE)+PAUSE
            GO TO 7
15          D=FLTS+D
            E=MEND+E
            FLY=D/A
            US=E/A
            AVAIL=100*(1-US/DAY)
            A=A+1
            IF(A.LT.101)GO TO 4
            WRITE(2,102)MTBF,MTTR,CAP,DAY,FLY,US,AVAIL
```

```
7       IF(TIME.LT.DAY)GO TO 5
        GO TO 15
10      RANE=AMOD(41.*RANE+17,100.)
        C=-MTTR*ALOG(1-RANE/100)
        IF(C.LE.(DAY-TIME))GO TO 8
        C=DAY-TIME
8       MEND=MEND+C
        IF(C.LE.PAUSE)GO TO 6
        Z=(C-PAUSE)/(CAP+PAUSE)
        NZ=IFIX(Z)
        Z=FLOAT(NZ)
        TIME =TIME+(Z+1.)*(CAP+PAUSE)+PAUSE
        GO TO 7
15      D=FLTS+D
        E=MEND+E
        FLY=D/A
        US=E/A
        AVAIL=100*(1-US/DAY)
        A=A+1
        IF(A.LT.101)GO TO 4
        WRITE(2,102)MTBF,MTTR,CAP,DAY,FLY,US,AVAIL
        PAUSE=PAUSE+30
        IF(PAUSE.LE.180)GO TO 21
        DAY=DAY+360
        IF(DAY.LE.1000)GO TO 19
        WRITE(2,300)
        CAP=CAP+20
        IF(CAP.LE.70)GO TO 20
        MTTR=MTTR+60
        IF(MTTR.LE.240)GO TO 30
        MTBF=MTBF+30
        IF(MTBF.LE.240)GO TO 40
98      FORMAT(10X,'AVAILABILITY ON COMBAT AIR PATROL',/)
100     FORMAT(10X,'MTBF   MTTR   CAP  DAY  FLY   US  AVAIL')

102     FORMAT(11X,F4.0,2X,F4.0,1X,F4.0,1X,F4.0,2X,F4.2,2X,F5.1,2
300     FORMAT(/)
        STOP OK
        END
        FINISH
14.53.07←
```

APPENDIX 5

MDC RELIABILITY STATISTICS

E R 1J L TO 31DEC78

		AIRCRAFT RATES						SUPPLEMENTARY RATES			
CODE	AIRCRAFT SYSTEM	ARISNG RATE	DEFECT RATE	DEFECT MHR RATE	NFF MHR RATE	OP EFFCT RATE	OP EFFCT MHR RATE	ARISING RATE	DEFECT RATE	DEFECT MHR RATE	NFF MHR RATE
	AIRCRAFT MECHANICAL SYSTEMS										
01	AIRBORNE LIFTING & TOWING	-	-	-	-	-	-	-	-	-	-
02	AIR CONDITIONING	26.6	23.0	209.0	20.3	.5	4.9	7.1	5.6	35.2	4.4
05	AIR SERVICES	2.9	2.9	12.9	.2	.0	.0	.3	.2	.2	.2
11	FLYING/OPERATIONAL CONTROLS	128.9	129.7	1461.9	75.8	3.4	70.0	19.0	16.1	55.6	14.5
12	FUEL SYSTEM (AIRFRAME)	118.9	109.1	1675.9	97.7	6.4	98.8	34.5	24.6	146.1	31.3
13	HYDRAULIC POWER	112.9	82.0	686.6	99.9	5.3	114.1	27.4	22.7	75.8	22.9
16	ALIGHTING/ARRESTOR GEAR	204.3	209.1	1338.1	74.0	7.7	140.0	36.9	55.4	195.9	4.1
19	OXYGEN	26.7	24.8	131.8	19.8	.6	7.1	11.0	5.8	25.2	15.1
21	PNEUMATIC	-	-	-	-	-	-	-	-	-	-
23	WATER/WASTE	-	-	-	-	-	-	-	-	-	-
77	SPECIAL FIT AIRCRAFT SYSTEMS	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
91	MK 17/20 FLIGHT REFUELLING	-	-	-	-	-	-	-	-	-	-
	SYSTEM GROUP TOTAL	621.2	580.6	5516.3	387.8	24.0	434.9	136.1	130.5	530.0	92.5
	STRUCTURE SYSTEMS										
09	FURNISHING AND INTERIOR EQUPT	-	-	-	-	-	-	-	-	-	-
31	STRUCTURES	-	-	-	-	-	-	-	-	-	-
32	DOORS	-	-	-	-	-	-	-	-	-	-
33	FUSELAGE	243.9	248.8	2624.5	54.3	2.1	225.3	6.8	6.0	16.8	6.7
34	POWER UNIT POD/NACELLE	-	-	-	-	-	-	-	-	-	-
35	TAIL UNIT	15.8	16.9	86.4	.4	.0	.0	.2	.2	.2	.0
36	WINDOWS	-	-	-	-	-	-	-	-	-	-
37	MAINPLANE/WINGS	36.9	38.0	256.5	8.0	.0	.0	.8	.8	3.5	.0
78	SPECIAL FIT (STRUCTURES)	-	-	-	-	-	-	-	-	-	-
99	AIRCRAFT	6.8	2.6	136.6	62.7	1.0	40.7	1.6	1.3	3.5	3.1
	SYSTEM GROUP TOTAL	303.4	306.3	3104.1	125.4	3.1	266.0	9.3	8.2	24.0	9.8
	PROPULSION SYSTEMS										
04	AUXILIARY POWER PLANT/UNIT	-	-	-	-	-	-	-	-	-	-
41	PROPELLERS	-	-	-	-	-	-	-	-	-	-
42	MAIN ROTOR HEAD AND BLADES	-	-	-	-	-	-	-	-	-	-
43	TAIL ROTOR HUB AND BLADE	-	-	-	-	-	-	-	-	-	-
49	ENGINE FUEL	-	-	-	-	-	-	-	-	-	-
52	ENGINE CONTROLS	-	-	-	-	-	-	-	-	-	-
53	ENGINE INDICATING	-	-	-	-	-	-	-	-	-	-
54	ENGINE EXHAUST	-	-	-	-	-	-	-	-	-	-
55	OIL SYSTEM	-	-	-	-	-	-	-	-	-	-
56	ENGINE STARTING	21.3	21.4	294.7	16.4	3.7	63.1	12.4	9.5	111.2	8.4
57	WATER INJECTION	26.7	25.0	210.4	13.1	.2	2.4	10.3	9.2	34.0	1.8
58	TRANSMISSION/GEARBOX FIXED WING	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
59	COOLING	-	-	-	-	-	-	-	-	-	-
60	PROPULSION/POWER PLANT	150.6	139.0	2884.9	212.7	9.8	251.0	39.1	31.7	677.3	27.0
61	TRANSMISSION/GEARBOX ROTRY WING	-	-	-	-	-	-	-	-	-	-
62	CONSTANT SPEED DRIVE	-	-	-	-	-	-	-	-	-	-
79	SPECIAL FIT PROPELLERS/ROTORS	-	-	-	-	-	-	-	-	-	-
80	SPECIAL FIT PROPULSION	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
90	REHEAT	-	-	-	-	-	-	-	-	-	-
	SYSTEM GROUP TOTAL	198.6	185.4	3390.1	242.1	13.7	316.5	61.9	50.4	822.5	37.1

		AIRCRAFT RATES						SUPPLEMENTARY RATES			
CODE	AIRCRAFT SYSTEM	ARISNG RATE	DEFECT RATE	DEFECT MHR RATE	NFF MHR RATE	OP EFFCT RATE	OP EFFCT MHR RATE	ARISING RATE	DEFECT RATE	DEFECT MHR RATE	NFF MHR RATE
	ARMAMENT SYSTEMS										
27	EMERGENCY EQUIPMENT	17.9	16.6	62.7	21.6	.2	.6	4.2	2.9	6.1	3.6
66	PYROTECHNIC AND SIGNL DISCHGERS	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
67	GUNS	14.8	14.0	86.7	8.9	1.9	19.9	6.4	5.8	30.6	3.3
68	OPTICAL SIGHTING	.5	.8	11.5	.6	.2	1.7	.5	.3	1.8	.6
69	GW/RP CARRIAGE AND RELEASE	1.9	1.3	6.4	2.5	.3	1.4	.2	.2	.5	.0
70	ARMAMENT STORES C AND R	17.9	15.9	127.3	28.9	3.2	44.9	6.1	3.4	12.8	15.1
72	ARMAMENT CONTROL AND GENERAL	11.3	10.5	77.4	5.8	1.1	9.6	2.4	1.6	4.9	1.8
73	SPECIAL WEAPONS C AND R	-	-	-	-	-	-	-	-	-	-
81	SPECIAL FIT ARMAMENT SYSTEMS	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
	SYSTEM GROUP TOTAL	64.3	59.1	372.0	65.3	6.9	78.2	19.8	14.2	56.7	24.3
	TACTICAL AVIONIC SYSTEMS										
05	AUTOMATIC FLIGHT CONTROL	17.1	15.5	274.4	29.8	.2	8.5	11.0	9.3	82.7	13.6
22	TACTICAL EQUIPMENT	-	-	-	-	-	-	-	-	-	-
24	FLIGHT/NAVIGATION/ATTACK	251.2	226.2	3284.7	745.2	12.9	230.6	147.3	86.2	1261.2	559.2
30	TACTICAL SENSORS	-	-	-	-	-	-	-	-	-	-
86	TACTICAL COMPUTING AND DISPLAY	-	-	-	-	-	-	-	-	-	-
87	ECM	11.4	10.0	129.4	19.2	.2	1.8	7.4	4.3	53.7	12.2
88	SURV, SEARCH AND IDENTIFICATION	12.7	11.1	83.7	20.8	.2	2.8	7.4	4.2	41.1	14.6
	SYSTEM GROUP TOTAL	292.4	262.8	3772.2	815.0	13.4	243.7	173.0	104.1	1438.8	599.6
	NAVIGATION AND COMMS SYSTEMS										
06	COMMUNICATIONS	64.8	55.6	603.2	77.8	10.8	132.9	28.5	30.4	310.5	46.5
18	NAVIGATION	-	-	-	-	-	-	-	-	-	-
25	RADIO NAVIGATION/LANDING AIDS	11.8	10.5	133.0	9.2	.3	1.0	6.6	5.0	93.3	6.1
	SYSTEM GROUP TOTAL	76.5	66.1	736.2	86.9	11.1	133.9	35.1	35.4	403.8	52.6
	ELECT AND INST SYSTEMS										
07	CENTRALISED WARNING	11.6	10.6	71.8	13.7	.3	5.9	2.3	1.8	17.1	2.0
08	ELECT POWER SUPPLIES AND DISTBN	72.0	73.9	416.2	81.8	4.0	71.5	20.9	10.8	45.8	47.8
10	FIRE PROTECTION	2.7	2.9	12.8	.0	.0	.0	.3	.3	.2	.0
14	ICE AND RAIN PROTECTION	8.5	7.9	63.2	4.1	.6	7.9	1.4	1.4	4.7	.0
15	GENERAL INSTRUMENTS	44.0	39.3	374.2	35.6	3.1	37.1	22.1	16.8	120.0	17.0
17	LIGHTING	40.1	40.0	292.0	3.3	.3	.8	12.1	11.8	79.9	1.7
28	ONBOARD CHECKING AND MONITORING	-	-	-	-	-	-	-	-	-	-
76	TRIALS INSTRUMENTATION	.6	.6	5.5	.0	.0	.0	.0	.0	.0	.0
	SYSTEM GROUP TOTAL	179.6	175.3	1235.6	138.6	8.4	123.2	59.1	42.9	267.7	68.6
	RECONNAISSANCE SYSTEMS										
20	PHOTO/RECCE PODS	-	-	-	-	-	-	-	-	-	-
89	PHOTOGRAPHIC/RECCE	16.6	15.5	86.0	7.6	.0	.0	5.3	4.3	18.5	4.9
	SYSTEM GROUP TOTAL	16.6	15.5	86.0	7.6	.0	.0	5.3	4.3	18.5	4.9
	AIRCRAFT COMPLETE	1752.7	1651.0	18212.4	1868.8	80.6	1596.4	499.8	390.0	3562.2	889.5

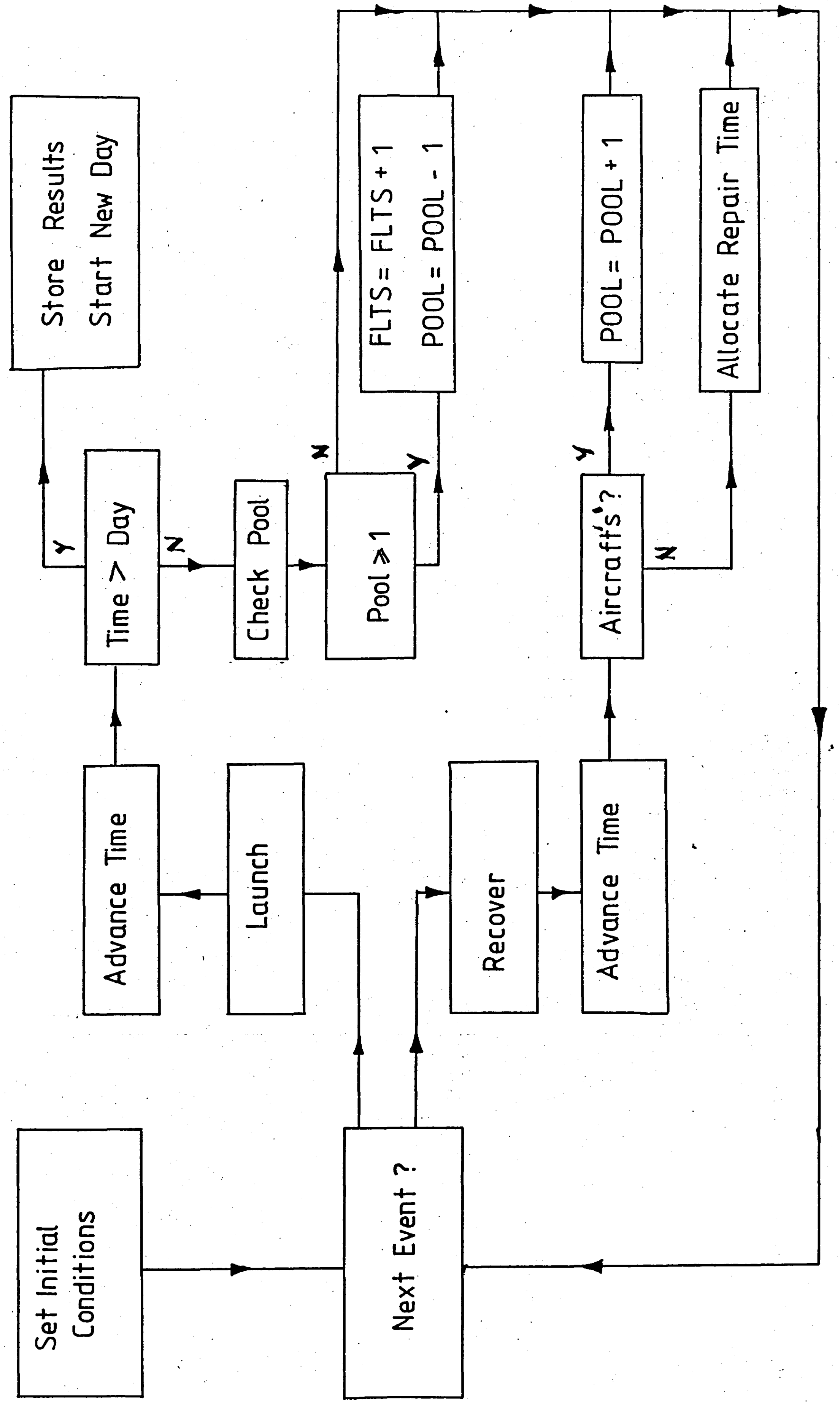
ALL DATA RATED PER 1000 FLYING HOURS

PROGRAM SCAU

```
      MASTER PROG
C     AVAILABILITY ON COMBAT AIR PATROL
C     TWO AIRCRAFT
C     MAIN CALCULATION
      REAL MTBF,MTTR,IX
      WRITE(2,98)
      WRITE(2,100)
      MTBF=30
40    MTTR=30
30    CAP=75
20    DAY=720
19     AND=50
      RANE=50
      PAUSE=15
21    A=1
8     XV=0
      XIV=0
      XIII=0
      XII=0
      XI=0
      X=0
      IX=0
      VIII=0
      VII=0
4      TIME=PAUSE
      FRED=DAY
      BERT=DAY
       HARRY=DAY
        GEORGE=DAY
      POOL=2
      CABS=POOL-1
      K=0
       LTS=1
41    IF(K.EQ.0)GO TO 66
      K=0
       TIME=TIME+PAUSE
      B=EXP(-CAP/MTBF)
      RAND=AMOD(21.*RAND+7,100.)
      IF((RAND/100).GE.B)GO TO 10
      CABS=CABS+1
      GO TO 41
10    RANE=AMOD(41.*RANE+17,100.)
      C=-MTTR*ALOG(1-RANE/100)
      IF(FRED.NE.DAY)GO TO 37
      FRED=TIME+C
      GO TO 41
37    IF(BERT.NE.DAY)GO TO 55
      BERT=TIME+C
      GO TO 41
55    IF(HARRY.NE.DAY)GO TO 56
      HARRY=TIME+C
      GO TO 41
56    IF(GEORGE.NE.DAY)GO TO 41
      GEORGE=TIME+C
      GO TO 41
66    K=1
      TIME=TIME+(CAP-2*PAUSE)
```

```
66      K=1
        TIME=TIME (CAP-2*PAUSE)
         IF(TIME.GE.DAY)GO TO 15
        IF(TIME.LT.FRED)GO TO 32
        CABS=CABS+1
        FRED=DAY
32      IF(TIME.LT.BERT)GO TO 43
        CABS=CABS+1
        BERT=DAY
43      IF(TIME.LT.HARRY)GO  TO  44
        CABS=CABS+1
        HARRY=DAY
44      IF(TIME.LT.GEORGE)GO TO 33
         CABS=CABS+1
         GEORGE=DAY
33      IF(CABS.GE.1)FLTS=FLTS+1
        IF(CABS.GE.1)CABS=CABS-1
        GO TO 41
15       IF(FLTS.EQ.15)XV=XV+1
         IF(FLTS.EQ.14)XIV=XIV+1
         IF(FLTS.EQ.13)XIII=XIII+1
         IF(FLTS.EQ.12)XII=XII+1
         IF(FLTS.EQ.11)XI=XI+1
         IF(FLTS.EQ.10)X=X+1
         IF(FLTS.EQ.9)IX=IX+1
         IF(FLTS.EQ.8)VIII=VIII+1
         IF(FLTS.EQ.7)VII=VII+1
        A=A+1
        IF(A.LT.101)GO TO 4
        WRITE(2,102)MTBF,MTTR,CAP,XV,XIV,XIII,XII,XI,X,IX,VIII,VI
98      FORMAT(10X,´AVAILABILITY ON COMBAT AIR PATROL´,/)
100      FORMAT(4X,´MTBF MTTR CAP    XV  XIV XIII XII   XI   X IX  V

102     FORMAT(3X,F4.0,2X,F4.0,2X,F4.0,1X,F3.0,1X,F3.0,1X,F3.0,1X
       A,F3.0,1X,F3.0,1X,F3.0,1X,F3.0,1X,F3.0)
300     FORMAT(/)
        MTTR=MTTR*2
        IF(MTTR.LE.960)GO TO 30
        MTBF=MTBF*2
        IF(MTBF.LE.960)GO TO 40
        STOP OK
        END
        FINISH
16.11.42←
```


Set Initial Conditions
Next Event ?
Launch
Advance Time
Time > Day
Y
N
Store Results
Start New Day
Check Pool
Pool ≥ 1
Y
N
FLTS = FLTS + 1
POOL = POOL - 1
Recover
Advance Time
Aircraft's'?
Y
N
POOL = POOL + 1
Allocate Repair Time

THE EMPLOYMENT OF JET V-STOL AIRCRAFT AT SEA

PART 5

SUPPORT AND LOGISTICS

SUMMARY

Aircraft on detachment have to be supported by resources of manpower and materials. The scale of this support echelon depends on the nature of the aircraft and also on its utilisation, and so has a fixed component, dependent on the size of the detachment and on the policy for scheduled maintenance, plus a variable component dependent on the flying rate and on the unscheduled maintenance. A major contributor to this variable component will be the range of weaponry to be delivered, and this can become the governing factor of the size of the whole support pack.

Scaling the support organisation is done by a mixture of art, based on unquantifiable experience and 'feel', and science, based on quantifiable experience such as defect and consumption data, but itself underpinned by judgement used in balancing the risks of a shortfall of spares against the cost of overprovisioning. Statistical data are available to provide a firm foundation for all such decisions and to reduce the guesswork to a minimum, and some basic models are already in use for stores provisioning. No statements of 'policy' should be accepted without question if they result in unbalancing the support package.

So the two brothers sent off hand in hand into the wood and returned in a minute with their arms full of things - such as bolsters, blankets, hearth-rugs, table-cloths, dish covers and coal scuttles.

'I hope you're a good hand at pinning and tying string?' Tweedledum remarked. 'Every one of these things has got to go on, somehow or other!'

INDEX

ANNEXES

INTRODUCTION

This study so far has shown that there can be a role in Naval Aviation for a V-STOL or STOVL aircraft, that an aircraft such as the Sea Harrier can take off from a small deck at an all-up-weight large enough to carry out a worthwhile mission and that the Sea Harrier itself can be Reliable and Maintainable enough to be able to keep up a repetitive flying programme for a useful period.

The task to be investigated now is that of working out what support is needed in terms of manpower, equipment and spares in order to sustain such a flying programme and make the whole exercise of operating V-STOL aircraft from sub-capital ships in penny packets a practicable proposition.

Wherever a specific aircraft type is considered in this section it is, inevitably, the Sea Harrier, and all equipment and scales of manning referred to relate to this aircraft. It is the intention however, that this paper should be able to be read across to any other aircraft type, real or projected, and the approach employed should serve as a demonstration model as well as a worked example.

It is one problem to site a V-STOL aircraft on a ship and fly it off again. It is quite another to equip that ship well enough to make the flying exercise a regular and dependable procedure. The aircraft perched in an Alert state on the flight deck represents the tip of an iceberg. It stays in sight only by the efforts of a submerged bulk greater than itself. The ingredients of this bulk are a support system, both near and far, of manpower, ground equipment, armament equipment, weapons, consumable and combustible stores and spare parts necessary to keep the aircraft tended and ready to operate. Between being able to fly and being able to operate there is a great gulf. How this gulf is to be bridged forms the subject of this part of the Maritime V-STOL study.

It is not intended to go as far as producing full ranges and scales of spares and equipment down to the last identifiable item. The object is to discuss and describe the processes by which decisions can be made on what level of support to aim for, on what to take and what to leave behind. The details can be filled in later when the task becomes a reality.

Levels of Servicing and Support

During the last couple of years there has been a certain amount of speculation by the Aviation correspondents of the Press on the subject of deploying Sea Harrier to ships other than the through deck cruisers. The possibility of detaching aircraft to a Merchant containership along the lines of the US Navy's 'Arapaho' project has been aired (Ref.1), and so has the idea of single-aircraft operation from destroyers, frigates and auxiliaries (Ref.2). The possible relevance of the Arapaho scheme will be discussed in the next Part of this study, and while it is doubtful whether any current or forthcoming designs of destroyers and frigates in the Royal Navy could ever hope to carry a Sea Harrier, (this, too, belongs more properly to the next Part), there are in existence schemes for adaptation of current designs expressly modified for Harrier operation, and not just transient operation but full support of small flights of aircraft. Even if these designs are not likely to be adopted by the Royal Navy, that does not exclude the possibility of their being commissioned by NATO or other allied Fleets.

Therefore the level of support and servicing which will be discussed will not be limited to what is necessary for operational Turn-Rounds on a ship acting in the role of a Forward Operating Base, but will be extended to cover deeper support on a private ship where appropriate.

MANPOWER REQUIREMENTS

First Line

The method used by the Royal Navy for estimating how many men will be needed for the support of a number of aircraft for a given period is a blend of mathematics and experience.

Mathematics follows the line used to solve problems of the sort which goes 'if three men can dig a hole in two days how long will it take five men to dig a hole twice the size?' It takes as a starting point the value of the estimated Manhours per Flying Hour. This is taken from recorded experience on aircraft of the same type as or similar to the type being considered, and the sources consulted are the Naval Aircraft Technical Evaluation Centre (NATEC) for the share of the load due to scheduled work, and the Maintenance Data Centre (MDC) for the contribution caused by Unscheduled work. (Before MDC was established the source likely to be consulted for the Unscheduled work load would have been the Naval Staff Requirement, and the target Manhours per Flying hour in that was based more on optimisation than on precedent. This was the procedure followed in the early days of planning for the Sea Harrier and nearly led to the complement and accommodation for the Squadron Manpower being far too little to be able to cope with the aircraft in the through-deck cruiser. Fortunately an injection of more realistic man-hour figures based on RAF experience with the Harrier GR3 was made into the model and the potential error was corrected in time).

Following on after the mathematics groundwork the intuitive approach takes over, scaling the raw man-hours up or down as necessary. Allowance is made for the facts that two men do not work on an aircraft twice as quickly as one man and that no man can ever be fully effective for the whole of his working day, as so many other calls are made upon his time additional to those meeting the demands of aircraft. The factor the Royal Navy applies to the available time in order to arrive at the effective time is termed the J-Factor.

This J-Factor sounds imposingly scientific and business-like, and its true origin is not widely known. It was devised many years ago by one Lieutenant-Commander 'Jumbo' Cramond, (now Captain ret'd). Part of his job was to work out Squadron manning levels and he recognised the need for a fiddle-factor which when divided into the man-hours he calculated he should have would give him the man-hours he knew he would get. This factor came out to be something of the order of 3½ - 4½. and he named it after himself on the grounds that, in his own words, "it is large and largely unnecessary".

What all this adds up to is that the only realistic way to work out the manning for a Naval Air Squadron and support Air Engineering Department is by inspection and arithmetic, both tempered by experience. This then is the method which will be applied in this study, and it will be expected that more than one answer will be reached in some cases, depending for instance on whether the flying intensity being prepared for is demanding enough to call for the Maintenance team to be required to work round the clock in a Two-Watch System.

Scales of manning will be worked out for hypothetical ship's flights of one aircraft and of three aircraft respectively.

Using the method of manning by inspection, the first thing to do is to establish what the most labour-intensive routine task is likely to be and work out a staffing figure for that. The leading candidate for this position is the job of preparing the aircraft for flight at the start of the day and at the same time loading them with, say, two Sea Eagles and two Sidewinders.

This job will call for a minimum of one A/E (Airframe/Engine qualified) Supervisory Rate on deck, one A/E Junior

Rate per aircraft, one A/W (Air Weapons qualified) Senior or equivalent and at least one A/W Junior per aircraft, (the balance of the loading team being drawn from ship's staff). Additionally two L/R (Electrical/Radio qualified) specialists, one Senior and one Junior, will also be required, but not necessarily at the rate of one for each aircraft.

Using this method the minimum line teams work out as follows:

	Single Aircraft	Three Aircraft
A/E	1 + 1	1 + 3
A/W	1 + 1	3 + 3
L/R	1 + 1	2 + 2
Total	6	14

These numbers are the barest of bare minima. They assume that the A/W specialist will carry out the inspections which are normally the province of the Safety Equipment rating, and that all the tasks of the Aircraft Handlers, i.e.Firesuit Men, Handler Drivers, Lift Drivers, etc will be shared among the Maintenance crew as necessary. This redundancy of the Handler trade is acceptable only when working on small numbers of aircraft. It assumes that a technician is not able to work on an aircraft which is in the process of being moved, ranged or spotted by the Handlers and that therefore he will be available to move it. This is not always necessarily so.

As a check on these apparently roughly-compiled figures, let us compare them with the formal scale of manning in use for the Sea Harrier squadron in a ship of the Invincible class (Ref.3). These ships are fully manned to give the aircraft, of which they carry five, full support at first and second levels for extended periods of detachment. The figures listed below are those appropriate to conditions classified as 'Exercise tension' and 'Extended tension', both of which are considerably more spartan than the manning scale for peacetime operation.

Work is conducted in two Watches, each Watch being composed of the following:

	Senior	Junior
A/E	4	7
A/W	1	3
L/R	2	6
Handlers	4	9

(The Handlers in the Invincible have duties additional to the Firesuit and Mechanical Handler tasks mentioned earlier. They also drive the Flight Deck tractors and the Lifts, act as Safety Sentries in the hangar, and staff the Hangar Control Room and Aircraft Control Room, the ACR being the planning centre for all aircraft movements in and between the Hangar and the Flight Deck).

Setting the Handler branch aside, then we are left with a maintenance team totalling 23 in each Watch to look after 5 aircraft. In proportion this can be scaled down to figures of 5 for one aircraft and 14 for three.

Another bearing on the single aircraft case can be taken from a study conducted by the Air Engineer Officer students of the Royal Naval Engineering College on the support for a small-ship detachment of a single aircraft (Ref.4). Their figure was no fewer than eight, having three A/E Juniors rather than just one. This seems rather generous, especially as when all goes well and the aircraft meets all its planned sorties there will be no employment for any of them for a large proportion of the working day.

So far no account has been taken of the possible task of the aircraft. It is felt that the aircraft operating on its own will not be expected to sustain a repetitive task and therefore its irregular operation could most likely be supported by the bare Line team of 6, working without substitutes, permanently on call, after the fashion of the crew of a Lifeboat. The detachment of three however could be tasked more routinely and repetitively there will always be work to be done when operations are in train, so manning should be at a level capable of supporting at least one Watch plus a Slip watch, and maybe even two watches.

Altogether then, the manning requirements at First Line could be said to be:

Single Aircraft	Three Aircraft
6-8 men	21-28 men

it being stressed that the 'peacetime' complements would be higher.

As a cross-check on the single-aircraft figure it can be seen to be of the same order as that for a single-unit single-crew Lynx flight, which is seven men strong.

AIRCRAFT SERVICING

Aircraft servicing comes under two main headings. The first is Scheduled Servicing, which consists of the periodic routine maintenance considered necessary to keep the aircraft in an airworthy condition, together with the servicings immediately concerned with preparation for flight, replenishment and weapon loading, and the inspection called for immediately the flying is over, these latter categories together being termed Flight Servicing.

The other is Unscheduled Servicing, which is another term for defect rectification. It can be taken as a rough guide that during flying operations the man hours called for on Scheduled Servicing and Unscheduled Servicing are about equal.

Aircraft servicing will be dealt with then under the headings of Periodic Servicing, Flight and Replenishment Servicing and Unscheduled Servicing. The first two main headings will be subdivided further into Trade Groups.

Periodic Servicing

Periodic servicing needs to be carried out after set intervals of days or flying hours. These intervals may be large enough to allow the aircraft to operate for a worthwhile period without any periodic servicing being required. Thus it can be acceptable to clear a whole batch of servicing bringing items forward where necessary, immediately before starting out on a detachment.

The next step is to see how big these intervals may be.

a. Airframe and Engines

The A/E schedule for an aircraft is always larger than that for the other trades, largely because defects in mechanical systems can be detected while they are not running, (compared with Electrical and Radio systems which do not lend themselves readily to being inspected,) and also because such systems are amenable to being tinkered with.

Little or no periodic servicing will be called up during a seagoing detachment apart from protective husbandry (q.v) The intervals between servicing actions are usually great enough to enable them to span the embarked period, and so most periodic servicing can be got out of the way while the aircraft is ashore. With the aircraft poised for action the normal schedule will be stripped of all but the most essential operations. What remains is usually termed Contingency Servicing, and is designed with the limitations of shipboard servicing firmly in mind.

It is a curious characteristic of military aircraft maintenance that, whenever a war or exercise posture is assumed, all those servicing operations which had been considered vital to the operational capability of the aircraft in peacetime conditions, (when it does not really matter whether the aircraft flies or not) have to undergo the most searching reappraisal to see whether they are still absolutely necessary in war, (when presumably it matters a great deal).

There is nothing particularly new in this. The idea of conjuring up an improvement in aircraft availability by getting rid of as much as possible of the servicing schedule was in use during the Second World War.

It was the Operations Research Section of Coastal Command who carried out a detailed investigation into the servicing procedures for the maritime patrol aircraft of their day in the hope of finding something that would help them increase their flying effort. They examined the defect rate in successive ten hour periods throughout the flying-hour based major servicing cycle, and found that the servicing activity not only failed to arrest the defect rate, it actually doubled it until the effects of disturbing the aircraft's systems had worn off. This made it a simple task to convince the Command that much of the content of the servicing schedule could profitably be dispensed with, and by the end of 1943 the intervals between major servicings had been doubled (Ref.5). Similar research was carried out within Bomber Command where it was shown that the intervals between successive Minor Servicings could be increased from 50 hours to 75 hours without any accompanying increase in the aircraft defect rate.

In times of peace the contents of the Servicing Schedule have a habit of getting bigger and bigger, and the lessons demonstrated by the Operational Research practicioners of forty years ago have to be relearned regularly every few years.

The basic A/E schedule is founded on calendar-based operations at intervals of 7, 14, 17 and 28 days, 15, 30, 45, 60 and 90 weeks and 6 months, and flying-hour based operations at 15, 30, 60, 120, 180, 240, 300, 500, 1000 and 1200 hours. The most frequent of these are also the least demanding in effort, so 7-day and 15-hour operations should not impose any problems while 14-day and 30-hour operations should impose only a slight one. The flexibility exercised in developing a Contingency servicing schedule can be relied upon to keep servicing requirements for an embarked detachment down to an acceptably low level as necessary, certainly as far as A/E servicing goes. A bigger problem may be posed however by the requirements for Aircraft Husbandry standards to be maintained.

Husbandry

Ever since periodic modernisation was discontinued as a Servicing Procedure in the 1960s, and Naval Aircraft have been required to reach lines measured in terms of years rather than in units, the inroads made by corrosion on the structural integrity of these aircraft have been an increasingly difficult problem to counter, and it is now realised that to expose an aircraft to open deck conditions in a small ship for any length of time is to open it to a very high risk indeed. Kingston-on-Thames have had no experience in building a Naval Aircraft since this problem came to be recognised, and early reports are that the Sea Harrier has a very poor watertight integrity. On the optimistic side however it should be recorded that the interior of the aircraft is finished to the same surface standard as the exterior, and maybe corrosion will be prevented successfully from the start. At present the Sea Harrier operators are investing a lot of effort in anti-corrosion measures and the corrosion Flexible Operations are not able to be suspended. Aircraft Husbandry therefore could pose a large, but as yet unqualified task on an aircraft detachment, unless the Operating Commander is prepared to accept a fall in the standard of the structural condition of the aircraft as part of the price of the detachment.

b. Electrical, Radio and Radar

The only periodic maintenance called up in the Electrical System likely to interfere with a detachment is the requirement to change the battery.

At present this is an operation that is required to be carried out at intervals of one month unless defects intervene. The Mean Time Between Defects for the battery is about 100 hours.

Air Radio and Radar equipment are serviced only on defect, the principle being, in the American term "If it ain't bust, don't fix it". Scheduled Servicing is called for only for the PTR 377 communications set and the IFF transfinder, both of which need to be pressurised every 14 days, and the Blue Fox radar, whose dessicant needs attention at the same time.

c. Safety Equipment

The Ejection Seat needs to be removed for servicing every 15 weeks. This is a fairly big operation and calls for the use of a fully equipped seat workshop. It is suggested that an aircraft would fly off when this servicing comes due. (Also, certain anti-corrosion measures call for its removal more frequently. See above).

d. Weapons

The following weapon types are considered:

Aden gun
Bombs
Sidewinder Air Intercept Missile - 9L
Skyflash AIM
Sea Eagle ASM
Rockets

(1) Aden Guns

These need to be unshipped and serviced every 5 weeks if they have not been fired, and every 800 rounds if they have. This can be stretched to 1600 rounds after periods of continuous firing use, as the reason for servicing is to clear the mechanism of combustion products which should not be allowed to lie. The gun carries 120 rounds per loading, so a servicing life of about 12-14 firing sorties is imposed. The gun removed could be replaced by a serviced spare, so a workshop facility would not be absolutely necessary.

(2) Bombs

Some bombs require no routine servicing other than pre-use assembly and fuzing. Other bombs require more elaborate husbandry and would most probably not be considered appropriate to sub-capital ship operations.

(3) Sidewinder

The missile is not tested in the ship. All that is done is to check its response to an IR torch when loaded to an aircraft. This policy of no-test was vindicated when of all the Sidewinders unloaded by Ark Royal at the end of her last commission and returned for Second Line Servicing, only 13% were found to be unserviceable, and many of those were suffering only from surface dents and damage.

The launcher assembly needs a functional test every 14 days if the aircraft is kept in a loaded condition. The test set fits in a standard RAE box, i.e. about 18" cube.

(4) Skyflash

The missile can be assembled before delivery to the ship and stored in its assembled state. It can be kept on a loaded aircraft for up to 28 days, after which it should be removed for Bay Servicing.

The launcher for the Sea Harrier is not yet in service, but if its servicing cycle copies that of the ADV Tornado then launcher servicing will present no problem at either First or Second Line.

(5) Sea Eagle

No servicing is called for at First Line and no Second Line servicing is carried out at sea, it all being done ashore by the RAF. The launcher needs testing every 14 days, the test set again fitting into an RAE box.

The missile may remain loaded to an aircraft for four weeks or more, and kept in open deck conditions for five days.

(6) Rockets

No servicing is required.

N.B. Ejector Release Units

At present ERUs should be removed for Bay Servicing after every firing. This requirement should lapse after modification action, which is currently in hand, has been completed.

Periodic Servicing - Summing Up

A detachment of up to 14 days can be managed in such a way that periodic servicing imposes scarcely any problems at all. Above 14 days a small amount of test equipment is needed, mainly for the weaponry. This implies that extra weaponry equipment might need to be embarked to cater for the cases of test failure. Spare serviced guns might also need to be carried.

Flight and Replenishment Servicing

The Harrier aircraft is specifically designed to be able to operate from forward sites for short periods with only a minimum amount of Ground Servicing equipment being required. Even so, this minimum is pretty substantial in practice, especially when the period of operation extends from one to many days. And when it is remembered that for every sortie it flies the Harrier must take on up to three tons of fuel and maybe more than a ton of ordnance it will be appreciated that logistic support is going to be no small problem.

The total amount of equipment and supplies required will be the sum of the 'fixed costs' and the 'variable costs' of the operation. The fixed costs will be a function of the number of aircraft deployed and the number of weapon types for which they will be configured, while the variable costs will be a function of the number of hours or sorties flown and the amount of ordnance delivered.

There are three studies already in circulation that can be used as starting points for finding out what we need to take and how big it all is.

The first (Ref.6) was produced by the then Hawker Siddley Aviation in 1977. It lists the provisioning required to support eight Sea Harriers (or six or four), and was evidently intended as a guide for those shipbuilders who were venturing into the design of ships with a Sea Harrier capability. The second was produced by NATEC (Ref.7) in 1978 in response to a tentative task from Head of Aircraft Department (Navy) who were looking into the support required for just two aircraft embarked, while the third, already referred to (Ref.4) drew heavily on the other two.

In some respects these have been overtaken by events, but they have been used as a basis for considering what to recommend for detachments of one aircraft and of three under the headings of ground equipment (fixed costs) and consumables (variable costs).

Ground Equipment

Even to tend a single aircraft the list of equipment necessary is quite formidable. It must include static equipment such as intake blanks, chocks, lashings and access ladders, replenishment equipment and a water - washing rig to help keep the engine free from corrosion, aiming and weapon preparation kit and a mechanical handler for moving the aircraft about the deck, for an armed and fuelled aircraft will weigh over ten tons and cannot be moved safely by shoulder power.

An initial list is summarised below and spelled out in more detail in Annex A.

Equipment and Stores Required for Routine Support of Detached Sea Harrier Aircraft

	Single Aircraft		Three Aircraft	
	Lb	Cu.Ft.	Lb	Cu.Ft.
Static Gear	380	30	1140	89
Replenishment gear (1)	2000	120	2280	143
Arming gear (2)	539	51	925	64
Mechanical Handler	4027	225	4027	225
Total 'essential' gear	6956	426	8372	520
'Desirable' gear	1540	75	1540	75
Total	4497	501	9912	595

Notes

(1) Includes an Oxygen charging rig. This assumes a gaseous oxygen system is fitted. Even this might not be necessary, (Ref.8), see later.

(2) Calculated for one heavy missile type only. Does not include handling and storage gear for Skyflash or Sea Eagle.

The lists of equipment making up the Table above are not absolutely rigid, and there is no doubt that a single aircraft could be detached for a day with little more than rearming kit to support it. However, it can clearly be seen that if it is to be supported for any length of time it needs to take more than two-thirds of its own empty weight away with it.

b. Consumables

Consumables will be listed under the headings of Fuel, Oil, Water, Oxygen, Weapons and drop-tanks.

Fuel The Sea Harrier carries about 4500 lb of AVCAT in its internal tanks and can load a further 1500 lb in its drop tanks. A working figure for fuel consumption can be taken to be 60 lb/min, so in round figures fuel will need to be provided at a rate of some 2 tons per flying hour.

Oil Oil consumption is quoted in Ref.6 as being only 5 lb per flight hour. Oil storage will present no problem.

Water (1) Engine Injection

Each aircraft carries 500 lb of demineralised water for thrust augmentation, and it is considered that all seaborne Harrier take-offs and landings will be 'wet'. This accounts for 240 lb per sortie, 140 lb for take-off and 100 lb for landing. Water of the right quality can be assumed to be available from steam driven ships, but some form of chemical purification will be necessary if the aircraft is to operate from one powered by diesel or gas turbine. The RAF uses a chemical water purifier weighing about 100 lb at its dispersed sites. The useful life of this equipment depends on the purity of the primary water supply.

(2) Compressor Washing

Daily compressor washing is essential if engine corrosion is to be kept at bay. This calls for about 70 lb of water per aircraft per day.

Oxygen

Like its shoreborne sisters the GR3 and the AV-8A, the Sea Harrier is fitted with a LOX (Liquid Oxygen) system for the pilot's breathing supply. Its 5-litre container is sufficient to last an aircraft all day, and so it is suitable for outfield operations in roles such as Ground Attack which are most likely to be exercised at low level and in daylight, but it needs to be replenished after that time.

A Naval aircraft always needs 100% Oxygen for taking off and landing, in case an accident puts it into the sea, and the Sea Harrier is meant as well to operate at relatively high levels where the oxygen content of the pilot's breathing air-mix is high. LOX itself is unstable and difficult to store, and altogether it seems that the Liquid Oxygen system is totally unsuitable for an aircraft detaching for relatively long periods to a sub-capital ship, unless that ship has its own LOX-making plant, which is very unlikely.

A GOX (Gaseous Oxygen) system would be far better. The endurance of a GOX system installed in the space intended for a LOX system will not be as great, but it will suffice for all missions other than long-range ferry flights with in-flight refuelling. So one solution to the problem would be to modify the Sea Harrier to take a GOX system. Fortunately this idea is not without precedent as a GOX system has been schemed as a fit for the Sea Harriers which are to be supplied to the Indian Navy.

Recently a very promising alternative to both LOX and GOX has come on the scene, and one that would remove the replenishment problem entirely. The new system consists of an on-board oxygen generating equipment which works by enriching bleed air from the engine compressor by use of a molecular sieve. Trials on this equipment were due to start in March 1980 and, happily, the aircraft type to be used as a test vehicle is to be the AV-8A (Ref.8), so if the installation is proved to be successful it would be immediately compatible with the Sea Harrier.

Weapons

a. 30mm ADEN gun ammunition. Standard ammunition boxes are about the size of beer crates and carry 30 rounds. So about 50 boxes would last the servicing life of the gun.

b. Bombs. Bombs are 200, 500, 540, 800 and 100 lb in weight and require proper magazine facilities. A Sea Harrier carrying 2 x 1000 lb bombs cannot execute a Vertical Take-off with full internal fuel and would have an operational range of little more than 50 miles.

c. Sidewinders. Each missile is about 9ft long and weighs about 200 lb. The aircraft normally carries them in pairs but adaptations could be made to bring the load up to two on each of five hardpoints.

d. Skyflash. Each missile is about 12ft long and weighs some 450 lb. They are carried in pairs, one on each inboard pylon. A safe stowage will be required for reload rounds.

e. Sea Eagle. The missile is stacked on its palletrolley which is also used for moving it around. Access to an upper stack calls for special magazine fit equipment. The dimensions of the palletrolley are approximately 3' x 3' x 15', so each round will require a storage space of nearly 150 cu.ft.

The Sea Eagle weighs more than the heaviest bomb and therefore the aircraft range would still be only about 50 miles. However the missiles' own range is more than as much again as this.

f. Rockets. These can be hand-loaded and stored on racks. Their storage should present little more difficulty than do the Ammunition boxes for the Aden guns.

Drop Tanks

It can be expected that in hot war conditions aircraft carrying light air-to-air ordnance will also carry drop tanks and jettison them when empty. Storage space will therefore have to be available for these, at a rate of about 100 cubic feet per pair.

Summary of Consumables

In round figures the major variable cost items required to support the detachment lasting 20 sorties of 1 hour each work out as follows:

Fuel: 40 Tons
Oil: 50 lb (say 1 x 40 gall.drum)
Water: Injection 3 Ton
Washing 0.2 Ton
Oxygen: 1 Bottle
Weapons:
a. VTO at 1500 lb per sortie : 15 Tons
b. STO at 2500 lb per sortie : 25 Tons

These weapon loads could range from 40 Sea Eagles to 50 Skyflash to 200 Sidewinders in the extreme case.

The sheer volume of the heavier weapons makes it very unlikely that aircraft in small ship detachments would ever be configured for anything other than light bombs, rocketry, or air-to-air warfare except for special occasions. The occasions will dictate the need but it is clear that when planning a Sea Harrier detachment the provision of weapon storage space and facilities must be given a high priority for consideration.

Scheduled Servicing - Summing Up

A single aircraft detached to a small ship for more than a day or so would require to be supported to the following extent:-

Manpower - Accommodation, office space and a communications/control system would be required for one pilot plus at least six Maintainers.

Ground Equipment - At least 3 tons and nearer 4, occupying a space of over 400 cubic feet.

Consumables - About 2 tons of fuel per flying hour, plus 0.2 tons of demineralised water, and a small amount of engine oil.

Weapons - Between 1 and 2 tons per hour. Storage space for each hour's worth could be as much as 300 cubic feet if the aircraft were engaged in the anti-ship role.

(Alternatively, space would be required to house spare drop-tanks).

Three aircraft would call for slightly more than three times the manpower, only slightly more ground equipment, and consumables and weapons at the same rate.

UNSCHEDULED SERVICING - DEFECT RECTIFICATION

Reliability studies and experience of the Harrier GR3 as related in Part 4 show that a certain amount of aircraft unserviceability must be accepted as inevitable, and so if the level of availability is to be supported then there must be some capacity for defect rectification. The question is, how much?

The availability figure on which the feasibility of operating in small detachments has been demonstrated depended itself on the Mean Time to recover from a defect being 4 hours or less, so our first objective must be to aim for, or preferably below, this figure.

We know from earlier analyses, Part 4 Table 16, that rectification of defects on the aircraft without removing anything takes only 3/5 as long on average as does rectification by replacement, and that rate is only about 1½ man hours per flying hour for defects in the field. So, we are stuck with an aircraft requiring 50% repair-by-replacement, we must concentrate first on keeping doen the delays that might affect these longer defects. Clearly the secret of success must be closely linked with adequate on-board provisioning of spare parts.

Apart from the results of accidents or battle damage, the most awkward spare part we might be called upon to handle is an Engine Change Unit.

The Risk of an Engine Change

Whenever the subject of supporting and operating a Sea Harrier from a sub-capital ship is raised in contemporary Naval circles there is never any shortage of advisers who helpfully point out that such a project is doomed to failure from the start because no small ship could ever be equipped to cope with the problem of carrying out an engine change if the need arose. So before considering how to handle any lesser defects as they arise, some time must be spent in considering this one in greater depth.

To change the engine in a Harrier requires that the whole wing is removed before the engine can be lifted out. While the manufacturer has demonstrated that the whole task can be completed within 5½ hours using a team of eight men, and while a mobile hoist has been developed to make the evolution possible in a forest clearing, (Ref.9), the fact remains that the task is still pretty daunting, and one well beyond the capability of an unaugmented small ship detachment to manage. (As far as can be ascertained this mobile rig has yet to be used in anger).

What is the likelihood of being faced with this task? The source of our answer is again the Data Bank of the RAF/RN Maintenance Data Centre, RAF Swanton Morley. We will look at the rejection rate of the engine of the Harrier GR3 in RAF service and from it try to predict what it might be if the aircraft were operating from a small ship instead.

Engine Life Data Analysis

Whenever an engine of a military aircraft of the United Kingdom is rejected, a copy of the Engine Rejection Signal is passed to MDC, so too is a copy of the 720B Aircraft Job Card association with the task, and also, in time, a copy of the Manufacturer's strip and overhaul report. This engine rejection data can be printed out in semi-narrative form, using a standard output called SMERSH (Swanton Morley Engine Rejection Signal Hive-off), while the 720B information can be accessed by means of the Defect

Interrogation Process as used in the Availability study presented as Part 4 of this Paper. Examples of both types of output are given at Annex 2.

Results

The SMERSH procedure was used to produce an Engine Change Summary for Pegasus 103 for the period November 1978 through November 1979. The flying hours for this period were approximately 16,500.

From this SMERSH output the following figures emerge:

Total engine rejection = 113
Total due to Life expiry = 33
Balance = 80

It can be assumed that no aircraft would be detached to a ship with insufficient life remaining on its engine, so rejection for life expiry can be set aside. This gives a first estimate of the MTTBUR of

$$16500 \div 80 \approx 210 \text{ hours},$$

which in turn gives an estimation of the probability of completing a detachment of, say, 50 flying hours, without having to face the problem of an engine change of

$$\text{Exp}(150/210) = 0.79$$

While not too alarming, this value is not too reassuring either. Maybe the chance of getting away with it can be shown to be even higher.

The next move is to take a closer look at the causes of these 80 rejections. They are as follows:

Cause	Number Rejected
FOD, Bird Strike	25
Engine stiff, blade rub	6
Nozzles stiff	3
Damaged blades, lacing wire, plenum chamber	16
Poor performance, control	12
Fails SI; EFDC*	8
High oil consumption	3
Oil leak	5
Water leak	2
Total	80

* Early Failure Detection Check, e.g. Magnetic Plug.

Are all these occasions for engine rejection of the sort likely to be encountered in our ship detachment? If they are, then the value of MTBUR ≈ 210 hours holds good and its implications with it, if not then maybe a higher, more optimistic figure can be reached.

Checks for blade rub and stiffness in nozzle systems, inspections for blade damage and broken locking wire, all these form part of the scheduled servicing carried out during Primary and Minor inspections and the like, inspections which would be completed and got out of the way before embarkation, and after which the engine would be expected to have a clean bill of health. (The one exception is the EFDC, currently carried out at intervals of 15 hours. In the period of review it accounted for only a single rejection.)

In an embarked environment FOD is easier to avoid, and given care, so are bird strikes. The causes for rejection that remain may account for less than half of the original tally, and the MTBUR expected afloat could be more than double the value measured ashore.

In order to look more closely at the question of what was going on when the rejecting defect came to light we must switch from the SMERSH output and consider instead the output provided by the Defect Interogation Process, looking at the entries under the columns headed WHEN/HOW FOUND.

The available DIP output covers a slightly different period from that recorded by the SMERSH report. (This is due to differences between the systems whereby data is entered into the files at MDC). It embraces a period of 15,200 hours, but this makes no real difference to the eventual outcome. The number of engine rejections recorded was 65, (setting aside those due to Life Expiry), indicating a value of MTBUR of 235 hours compared with 210 hours calculated from the SMERSH approach.

With formally conducted defect hunts out of the way, the only causes of engine rejections likely to be encountered are reports from Aircrew, and defects found during Flight Servicing. A breakdown of these from this output is given overleaf.:

Symptom	Found by Aircrew	Found by Flight Servicing
a. FOD	2	11
b. Smoke in cockpit	2	-
c. Oil/Water leak	1	3
d. Parameter out of limits	5	6
e. Damage/Vibration	5	1
f. Blade rub	-	2
Total	15	23

Total 48

Thus, the most pessimistic analysis of the probability of an aircraft becoming stranded on deck because of the need for an engine change gives a rate of 48 occurrences in 15,000 hours, or about 1/300 per flying hour.

At the other extreme we can look at the rate at which the incident was considered serious enough to merit being reported on an Incident Signal. Here there were 10, which break down as follows:

Avoidable FOD: 2 (Intake blank and Telebrief cable ingested on startup)

Possible avoidable FOD: 2 (Intake door hinge bolt ingested on startup; steel strip from intake compressor seal ingested on approach).

Operational FOD: 3

Pilot Error: 1 (Failure to observe Red line entry regarding water pump limitations)

Possible Pilot Error: 1 (Undemanded shut down on landing, engine changed as a precaution)

Engine Blow-back: 1 (Damage to plenum chamber)

The most optimistic analysis of the data would lead to a risk rate of 3 or 4 per 15,000 flying hours, about 1/4000 per flying hour.

The true rate, as far as there can be one, will lie between these extremes. It might be considered safe, for instance, to get one more flight out of engines whose performance parameters were slightly outside the prescribed limits, the oil and water leaks might not be too serious to preclude one ferry flight, the FOD rate at sea might be only half that ashore. If these were so, then the final rate would be about 25/15,000 per flying hour, representing a risk of 1/600 per flying hour.

Translated into probabilities of servicing a detachment without needing an engine change on site, these figures give 98% for a 10 hour detachment and 90% for a 50 hour detachment.

These figures need not be refined any further. The message they carry is that the chance of being faced with the problem of an engine change during a detachment is very low, only about 1 in 10 for a 50 hour exercise. That risk should be well offset by the benefits gained from having those aircraft embarked.

SPARES AND REPLACEMENT PROVISIONING

The methods of provisioning spare parts for aircraft of the Royal Air Force and Royal Navy have, in the last ten years, undergone a shift in emphasis from being a dubious art to becoming a near science. The main factors in bringing this shift about have been the introduction of computer techniques, especially the application of Linear programming, as a means of making the stores list as effective as possible while keeping it as short and cheap to supply as possible, and the establishment and growth of an accessible Data Bank of defect and replacement information providing a source of raw material on which these tools can work.

The scientific methods which have been developed are not, however, applied in cold isolation from the older techniques. Art and judgement still have their part to play, especially when planning the support of aircraft engines, avionic systems and armament equipment.

Provisioning for the Harrier in RAF service has been a continuing task for many years, and the banks of defect data and of recorded experience have grown fuller side by side. These offer a valuable facility for initial and repeat provisioning for the Sea Harrier where its equipment is in common with that of the RAF Harrier. At the time of writing, however, (March/April 1980) the provisioner for those equipments and installations which are exclusive to the Sea Harrier is not so well served. The defect data bank for the Sea Harrier contains less than one year's worth of information based on only a handful of aircraft, and what little it contains is not really a representative forecast of what the spread and disposition of its contents are likely to be in the years to come.

Therefore there is no intention at this stage to attempt to produce a list of spares recommended for Sea Harrier detachments sometime in the future. The aim instead is to discuss how that task should be handled both for the Sea Harrier and for any other hypothetical future aircraft should these detachments of one unit or of three come to be called into being. The RAF already used a system of provisioning for detachments, stocking what they term a Tactical Flyaway Pack (TFAP - Ref.10). The method of building up a TFAP will be touched upon, but as some statistical weaknesses have been detected in it, an alternative method of provisioning for a detachment is developed and described. RAF data will, however, be used as illustrations where appropriate.

No scheme for aircraft spares provisioning can ever give absolutely the right answer. Ten to fifteen years ago, provisioning for Naval Aircraft was carried out rather pedantically, making heavy use of out-of-date formulae.

The results were not efficient, largely due to reluctance to make use of the defect feed-back information that was available at the time. Now better data can be accessed and more intelligent use is made of it. The provisioning levels which result will still not be perfect, but the degree by which they are in error will have been forecast in advance and accepted by the Command as the price of economy.

Fundamentals of provisioning for aircraft detachments

The job of the provisioner is to identify the members of two related families of unknowns. These are the answers to the questions:-

What bits must be supplied?

How many of each must be supplied?

The approach to the first is termed Ranging, while that to the second is termed Scaling. Ranging and Scaling for a new aircraft on introduction to service must be done almost entirely by the application of experience and judgement, but even in the case of an entirely new type of aircraft there is some prior knowledge available to be used as a foundation. Information such as the defect performance of similar equipments produced by the same manufacturer, the effect on the defect rate of operating in one aircraft environment as opposed to another, can be combined to give a defect or replacement rate fit for use for initial provisioning to an acceptable level of confidence.

The task of ranging and scaling for an update of provisioning for an aircraft which has been in service long enough to have accumulated a thorough service record is far simpler. It can be refined into one of getting the range and scale of stores right for the applications in hand, of not listing too little or too much, of balancing the risk of running out against the expense of carrying too much. There is a data bank of information of the defect history of the aircraft type, and every occasion on which a replacement part has been fitted will be recorded in it.

The rate at which things go wrong, the number and identity of those things which are most likely to go wrong, the implication of not having a replacement part to hand, the cost of buying the spares, all these are the ingredients which, when properly mixed, constitute a policy for spares support.

Stated more formally, they are:-

a. The rate of occurence of defects requiring parts replacement.
b. The identities of those parts
c. The fill rate accepted by the Command.

d. The degree of essentiality of each item
e. The cost of each item.

a. The Defect Rate

The defect rate that concerns us here is the rate per flying hour at which unserviceable items have to be removed from the aircraft and replaced by serviceable ones. As a great many defects can be remedied without removing anything from the aircraft at all, the rate we are looking for will not be as high as the encompassing defect rate on which were based the calculations for Reliability and Availability covered in the previous sections of this Study. The rate of defects requiring item replacements will vary within the aircraft from System to System; problems with Flight Instruments for instance being more liable to rectification by unit replacement than Engine System probelms which are able to be cured by adjustment.

In an established aircraft type such as the Harrier now, and the Sea Harrier by the time this is put into effect, the value we are seeking is the Mean Time Between Unscheduled Replacement (MTBUR), the reciprocal of the replacement defect rate. The defects we wish to count are whose whose Job Cards (F720B) have anything recorded in the Action Taken Field other than 'Rectified-in-Situ'. Therefore, in practice, the rate can be determined by subtracting the number recorded 'Rectified-in-Situ' from the total of all confirmed defects, dividing bv the Flvina Hours and then applying a correction for sampling errors. On some types of equipment, however, notably armament installations, the number of hours flown will not necessarily be a suitable measure against which to assess the MTBUR, and some other figure will have to be substituted, the number of weapons sorties for example. This is an instance of where experience still retains an edge over the computer.

This is the initial step taken by the RAF in establishing the makeup of a Tactical Flyaway Pack. The figure they use in thir compilations is a raw figure for MTBUR as supplied by the Maintenance Data Centre. This is the first weakness of the TFAP. MDC simply divides hours by events and calls the answer a 'Mean Time Between - ". In the extreme they are on record as dividing 15000 flying hours by one event and attributing the item concerned with an MTBUR of 1500 hours, which figure goes on into the further calculations. No correction is allowed for the error introduced by the size of the sample.

Given a stated number of events in a stated number of hours it is obviously easy to calculate an estimate of the Mean Time between events, but it must be stressed that an estimate is all that it is. This point is all too easily overlooked, and practioners then readily fall into the next trap of regarding an MTBUR of say 50 hours as implying that replacements fall due every 50 hours or so. The fact is that the accuracy of the estimate is itself dependent upon the number of events. An estimate of an MTBUR of 50 hours based on 20 events in 1000 hours is much nearer to the truth that one based on 2 events in 100 hours, and some measure of this accuracy (or, to be correct, inaccuracy) must be brought into subsequent calculations.

We assume a random distribution of events, i.e. that the time at which the next event occurs is independent of the time at which the previous one happened. We assume that a true value of MTBUR exists and that we can use our estimate to find it, and the approach we make is to look for a value of MTBUR such that our estimated value would not have been exceeded with more than 10% probability, say. The MTBUR quoted would then be at a Confidence Level of 90%.

It can be calculated by using the expansion of the Poisson Distribution, or, more readily, by reference to tables or charts. A suitable presentation in chart form is at Ref.11.

To illustrate this point, consider the case of having had 5 replacements in 1000 flying hours. This gives an untreated value of MTBUR = 200 hours. Use of the 90% confidence level chart at Ref.11. leads to a 90% confidence value of 125 hours. This means that an item with a true value of MTBUR = 125 hours could display a failure rate as low as 5 in 1000 hours with a 10% probability. Conversely, there is a 90% chance that the MTBUR is better than 125 hours. So if spares were provisioned on a basis of an MTBUR value of 125 hours we would have a 90% chance of being safe, whereas provisioning on a basis of 200 hours would have only a 50% chance of being right, ie an even chance of being wrong.

If instead of 5 events in 1000 hours we were working on 50 events in 10,000 hours the value of MTBUR at 90% confidence would be 172 hours, much closer to the raw estimate of 200 hours than the value based on only 5 events.

In the extreme case of only one event in 1000 hours, the 90% confidence value is about 200 hours. This means that the result of one failure in 1000 hours could have come with 10% probability from an item with a true MTBUR of only 260 hours, and certainly that to ascribe a value of MTBUR = 1000 hours on such fragile evidence is to be excessively optimistic.

So our first step in reprovisioning for an aircraft backed by a usable data bank is to interrogate that bank to deliver a range of items together with their values of MTBUR, and the second must be to apply a correction to these values, based on the number of replacements.

b. Item Identities

The best source of information from which to derive a range of values of MTBUR is as full a defect history of the aircraft as can be accessed. Given a full enough history it is possible to interrogate the bank for data from detachments similar to that being planned for, and thus get rates representative of action conditions, in much the same way as engine data was shown to be of more value when related to conditions to be expected.

With the Sea Harrier not yet in operational service, with, in fact, some of its operation systems still awaiting flight evaluation, the data available is of little or no value as yet. But to demonstrate how the provisioning task for small detachments should be handled, reference can be made instead to data generated within the RAF by its experience with the Harrier GR III.

The data for demonstration covers some 15000 hours experience. Applying a 90% confidence factor to items which required replacement only once shows that the highest MTBUR at that level is about 4000 hours. Items with an MTBUR higher than 4000 hours have yet to declare themselves.

The failure distributions of items within an aircraft follow a Pareto curve in that at one extreme there are a few items which each fail many times and at the other is a large number of items each of which fails only once or twice. The same sort of distribution is followed by those items which fail, and having failed, are rectified by replacement.

Replacement data for items within the RAF Harrier GR III are plotted at Fig.1. There are 13 items each of which was replaced 100 times or more, and at the other extreme there are 94, each of which failed 5 times or fewer. The degree of steepness or shallowness of this curve is important, for on it depends the possible thoroughness and cost of the provisioning exercise, together with the chance of its success.

In the Harrier GR III the number of items identified is only 327, and it is safe to forecast that a similar number would be identified in the Sea Harrier. This is encouraging because it means that even if the case for or against the provisioning of every item had to be discussed individually the size of the job would not make it completely unmanageable.

This data is plotted again in Fig.2, this time cumulatively. This shows that, if items failed at average rates, as distinct from rates which are themselves distributed randomly, as much as 50% of the demands could be met from only 10% of the range of items. As the

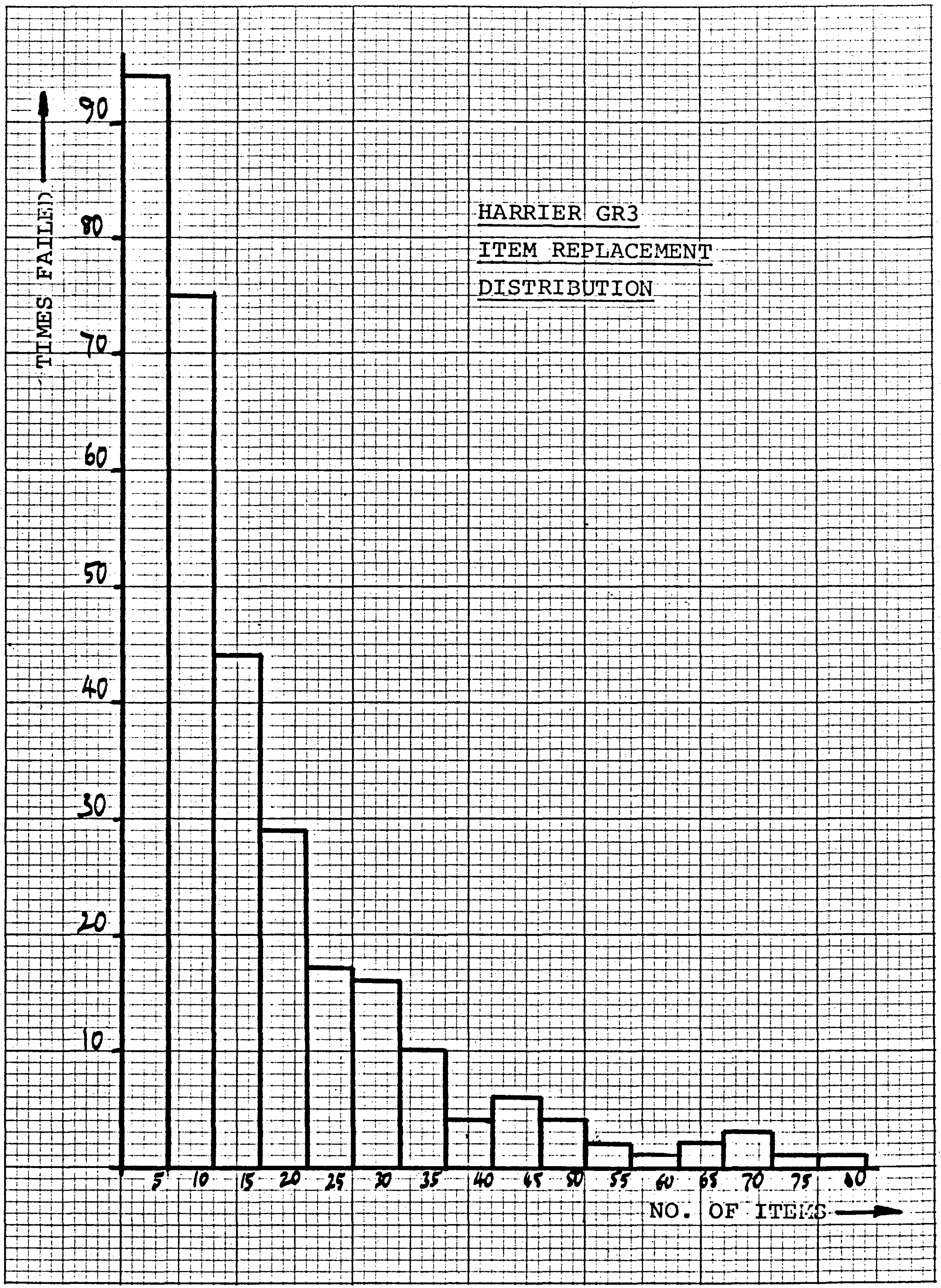
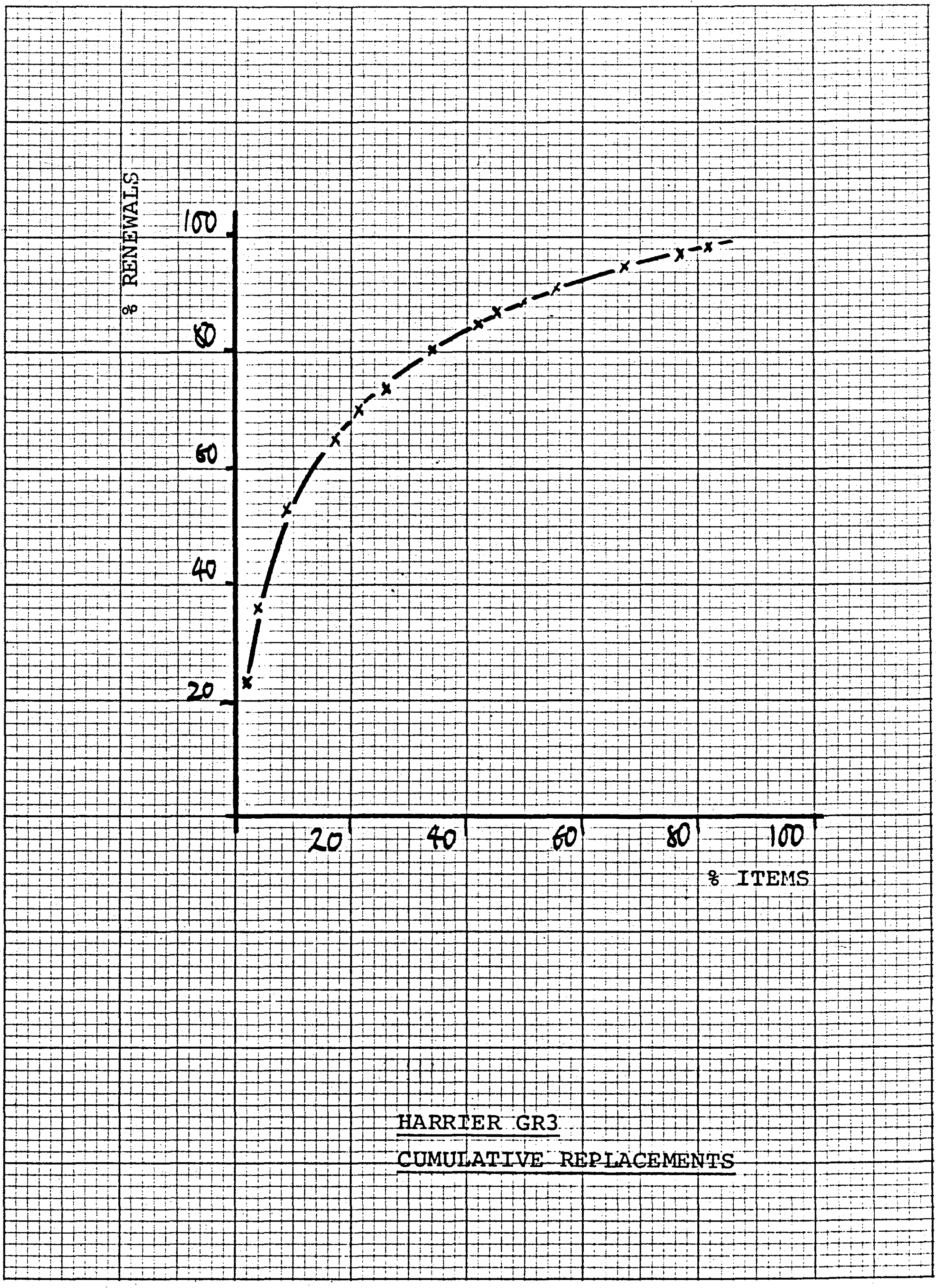

HARRIER GR3
ITEM REPLACEMENT
DISTRIBUTION
TIMES FAILED
90
80
70
60
50
40
30
20
10
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
NO. OF ITEMS

FIGURE 1



HARRIER GR3

CUMULATIVE REPLACEMENTS

FIGURE 2

proportion of demands to be met increases it can be seen that the range of items required to satisfy them increases also, but at an accelerating rate. Cover at a level of 75% calls for the initial 10% of the range to be increased to 26% and cover at a level of 90% calls for more than twice this much. An increase in cover beyond 90%, if it were required, would need to be justified against a disproportionate increase in the number, and therefore cost, of the different identities of items which would need to be added to the list.

In its explanation of the Fly-away Pack System, Ref.10, the RAF uses this example of diminishing returns to justify an economical cut-off in the range of spares to be recommended. If items failed at regular intervals, and if the proportion of the Pareto curve were not taken into account then this justification would be wholly valid. As we shall see later however, this approach is rather a simplification of that needed to give a statistically accurate cover.

So far, then, we have a list of identities of items which are vulnerable to replacement, together with a measure or distribution of how their degrees of vulnerability compare. Next we must look at how to decide how many to take.

Fill Rate

The fill rate is the probability of a demand being satisfied (Ref.12), so the higher the fill rate the greater will be the numbers of items in the Flyaway Pack and the greater too will be its cost. Because of the phenomenon of diminishing returns there will be a level of fill rate where the fill rate expressed as a percentage divided by the pack cost starts to fall away. This is the fill rate value which is usually aimed at.

If the detachment length in flying hours is multiplied by the replacement rate for each identified item the figure arrived at will be the average expected useage for each item. Being an average, this useage is just as likely to be exceeded as fallen short of. What is required is an average supply plus a little bit extra to give, say, an 85% or 90% chance of not missing out. This percentage is what is defined as the Fill Rate, and so, if the provisioning level was founded on only the average expected useage, the resulting fill rate would be 50%.

Provisioning to meet a given fill rate, other things being equal, is carried out by reference to the characteristics of the Poisson Distribution. Starting with the average expected useage as worked out above. Poisson tables can be consulted to find a provisioning scale such that the required fill rate is achieved or just exceeded. For example, using the tables in Ref.13 (but any other source of Poisson data will do), if the expected value of useage was 5 (e.g. an MTBUR of 30 hours and a detachment of 150 hours), it will be seen that the chance of experiencing 7 or fewer events is 86.7% and the chance of 8 or fewer is 93.2%. Therefore a stock of 8 would give protection right up to the 90% fill rate level and indeed slightly beyond. As the degree of statistical confidence in the value of MTBUR has already been stated, (90% in this study), then the product of this value and the Fill Rate will be a value of the success probability for each item considered.

Low useage items

The biggest problem in forming up a flyaway pack appears to be that of making the right decision about whether to take an item whose probability of being used is very low, i.e. an item fairly well up on the curve of diminishing returns. The RAF in their system of scaling flyaway packs has a simple and straightforward approach to this. Their approach is to exclude anything that has an 'outside chance' of failing during the planned number of flying hours. They define an outside chance at the level 20:1 or worse, and seek therefore to discard items whose failure probability is less than 5%.

For an item with MTBUR = M the probability of flying for a period of N hours without a failure is

$$\mathrm{Exp}\,(-N/M)$$

To meet the discard criteria then, we need to solve

$$\mathrm{Exp}(-N/M) = 0.95$$

from which $M = 20N$

This cut-off figure, e.g. no item with an MTBUR equal to or greater than 2000 hours shall be taken as a detachment of 100 hours, is applied to the ruling of the design of the TFAP. As it stands, however, this ruling is not quite as sound as it might be.

There are two reasons for caution:

(a) The value of MTBUR used has been based on simple division, whereas the necessity for a correction based on sample size has been explained already.

(b) No account has been taken of the distribution of values of MTBUR, that is, no account has been taken of the proportions of the Pareto curve. A simple example will serve to illustrate the point.

Consider an aircraft with an overall MTBUR = 1. This could be due to it consisting of any of the following:-

(i) 1 item with MTBUR = 1
or (ii) 10 items with MTBUR = 10
or (iii) 100 items with MTBUR = 100
or (iv) 200 items with MTBUR = 200

If it were to go on a detachment of duration 10, at the most elementary level the items provisioned for it would be 10 items of class (i), (ii) or (iii). Either way it would suffer an expected value of 10 occasions for spares replacement. But if it consisted of items from class (iv) then no spares at all would be taken, because no individual items would have a probability of useage greater than 5%. Clearly then some considerations should be given not only to investigating the upper value of MTBUR but also to considering how many items, or what proportion of the whole, have values above it. If there are only one or two then their exclusion can be fairly justified. If however there were ten, then the probability of not needing any one of them would be

$$(0.95)^{10} = 0.6$$

meaning that over the whole detachment there would be a significant (40%) chance of a shortage based on at least one member of the class.

High useage items present no problems as the statistical decision on their provisioning usually hinges on whether to supply say 7 units or 8. The problem lies in the area where the decision is that of whether to take 0 or 1. When resolving this decision notice must be taken of what proportion of the total spares candidature cames within this area.

The solution must be taken with reference to the Failure Rate distribution. For example, the Harrier GR III data from Fig.1 is tabulated below to give a distribution of MTBUR values at the 90% confidence level.

Corrected MTBUR Range	No. of Items
Less than 200 hours	25
200 - 400 hours	31
400 - 600 hours	49
600 - 800 hours	32
800 - 1000 hours	26
1000 - 1200 hours	34
1200 - 1400 hours	25
1400 - 1600 hours	11
1600 - 1800 hours	18
1800 - 2000 hours	19
Greater than 200 hours	57

TABLE 1

Planning for a detachment of 100 hours and applying a cut-off of 2000 hours then, the number of items excluded from the spares inventory would be 57.

The probability of not needing any of these would be

$$(0.95)^{57} = 0.05$$

so there is a 95% chance that at least one would be required, and therefore some provision ought to be made for at least some of them.

A suggested solution is to regard them all as comprising a single class with a MTBUR of, in this case, 35 hours.

Then the expected useage in 100 hours is 2.8 and the figure to achieve a 95% fill rate will be, from the Tables in Ref.13, 5. This means that at least 5 items from this range ought to be provisioned. The criteria on which to select these will be essentiality and cost.

The same can be done by considering the other class intervals in the same manner.

Essentiality

It is of course quite safe and possible to continue to fly the aircraft even though some systems may be defective, and therefore many items which have a high useage rate in normal service might not need replacing at all if they fail during a period of detached service.

The RAF recognises two classifications of essentiality: (Ref.12)

(1) Vital. A vital item is one which must be serviceable for an aircraft to takeoff, complete its operational mission and return.

(2) Desirable. A desirable component is one which, when defective, does not immediately prejudice the success of the aircrafts operational mission, but which may have to be replaced later during the deployment when its cumulative effect with other defective items would restrict operational capability.

To decide which items are truly vital is the prerogative of the Operational Command, and a list of items whose inserviceability is acceptable within certain limits is published in the Harrier Topic 6E-Battle Damage A.P. This is analagous to the Minimum Equipment List (MEL) laid down by operators within the Civil Airlines.

It is not the declared intention of the RN to produce a formal list of acceptable deferred defects in this manner. It is preferred to delegate the decisions as they arise to the operator on the spot. Thus when a detachment is to be planned, and the spares list derived from historic defect data and refined mathematically to suit the length of the detachment is produced, it will be subjected to a measure of judgement based on experience before becoming finalised.

Size of the detachment spares package

The RAF uses the techniques described here to produce a first list of items and the number of each that might be required to meet a stated fill rate. They ascribe categories of essentiality to each item and record its weight, volume and cost. All these data are then run on an optimising model TFAP 5 or 6 (for unsupported and supported detachments respectively) with other constraints imposed if required.

Such constraints can include rules that all Vital items not excluded by the MTBUR cut-off should be scaled at at least one copy of each, that the range of items should be as wide as possible, i.e. that items A and B should be listed rather than two items A, all else being equal, that the packed volume and/or weight should be less than certain limits imposed by air transportability.

The output is an optimised mix of items for the constraints imposed.

The TFAP for the Harrier GR3 for about 200 hours at a fill rate of 85% includes about 120 different items weighing altogether about 3 tons with a volume of about 300 cubic feet. This includes large items such as Generators and CSDU combined, together with built-up Aden guns. For the size of Sea Harrier detachment considered here the range and scale will be far smaller.

All the same if we apply the cut-off value of MTBUR of 20 x flying hours, we can see from Table 1 that the number of different eligible items is 183, and it is reasonable to assume a similar number for the Sea Harrier for a similar period of flying.

Avionic Support

It is very likely that the greatest source of unreliability will be somewhere in the aircraft's weapon and avionics system. Even for a short detachment it might be necessary to be able to rectify part of the system and this will call for test equipment as well as replacement Line Replacement Units. There are only six different Test Sets required for all the avionics, covering UHF, ESM + RADALT, IFF, I-Band transponder, Forward Looking Radar, and TACAN. (HUDWAC has Built-In Test Equipment), so finding space in a ships workshop for some or all of them would not be too difficult. What would be difficult however would be obtaining Test Gear at the rate of one outfit per detachment when it will already be provisioned only for known Ships and Squadrons.

The need to provision any of this equipment, test sets or spares, can only be judged when enough reliability data have been gathered at system and module level. It will be necessary to amass a data bank representing nearly 4000 hours' of operation before those items with an MTBUR of 1000 hours can be identified at a confidence level of 90%.

If a particular area of the weapon system shows itself to be especially prone to defect occurences, it may prove necessary to provide a rectification facility for even the shortest of detachments.

CONCLUSIONS

There is an enormous difference between flying an aircraft from a ship and operating that aircraft from the same ship. This difference is measured in terms of servicing equipment, manpower, fuel and consumables, weapons and spares. The amount of support required for a detachment can be decided only when the duration of that detachment is known and the tasking of the aircraft has been defined, but some generalisations hold good almost regardless of these dimensions, and those appropriate t the Sea Harrier are listed below.

Servicing Equipment

A single aircraft needs about three Tons of G.S.E. occupying about 400 cubic feet of space.

A flight of three aircraft needs only about one Ton more, plus a further 100-150 cubic feet.

Scheduled Servicing

Scheduled servicing need not impose any extra burden on the maintenance team for detachments of up to 2 or 3 weeks. After that the load would increase, but introduction of Contingency Servicing, which can be based only on further experience of the aircraft than has been gained so far, should keep it within manageable proportions.

Keeping up adequate husbandry standards could, however, be difficult. It depends on how much deterioration the Command will accept in return for the forward availability of the aircraft.

Manpower

A single aircraft could be maintained for a period of short bursts of operation, as from a Forward Operating Base for instance, by a team of only 6-8 men.

A flight of three would need about 21-28 men. Both these figures are the minima for wartime or intensive exercise conditions of operation, and would need assistance from the ship's company for arming activities and workshop support. The ship would have to accommodate and administer them all.

Fuel and Consumables

Aircraft fuel will be required to be supplied at the rate of 1.5 - 2.0 Tons per flying hour.

Demineralised water will be required at the rate of 0.2 Ton per flying hour.

Liquid oxygen is unlikely to be available. For detachments longer than one day the aircraft will need to be able to use a gaseous oxygen system.

Weapons

The weapons outfit will depend on the nature of the task of the detachment. The sheer bulk of some of the weapons available may present a major storage problem.

In hot war conditions aircraft drop tanks are likely to be used and expended. Spares take up a lot of space.

Spare Parts

Spares provisioning must be based on the data bank of recorded defect experience. Statistical methods can be used to take the first cut at the provisioning task, but the spares useage distribution does not follow a strict mathematical pattern and so scientific method must give way to subjective judgement when refining the spares list. However the range of spares will not be overwhelmingly great, a hundred or so different items would meet deficiencies encountered during a 50 hour detachment.

Deploying a lot of detachments at the same time might make excessive, even impossible, demands on the total buy of spares and test equipment.

The risk of needing to change an engine during a detachment of 50 hours is low enough to justify making no provision for it.

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ANNEX A

GROUND SERVICING EQUIPMENT REQUIREMENTS FOR SEA HARRIER DETACHMENTS

List 1. Essential Equipment

Item	Per Aircraft			Per Three Aircraft		
	No.	Wt. Lb.	Vol Cu.ft	No.	Wt Lb	Vol Cu.ft
STATIC GEAR						
Covers,Blanks,bungs	1 set	200	10	3 set	600	30
Cockpit access ladders	1	50	10	3	150	30
Lock nose u/c door	1	2	1	3	5	1
Pylon safety pins & warning plates	1 set	10	5	3 set	30	15
u/c safety lock	1	7	1	3	21	3
Lashings	1 set	50	1	3 set	150	3
Chocks	1 set	62	2	3 set	186	6
Sub Total		381	30		1142	88
AIRCRAFT REPLENISHMENT & SERVICING						
Flat top ladder	1	80	10	2	160	20
Risbridger gun, engine oil	1	50	2	2	100	4
Risbridger gun, hydraulic	1	40	2	1	40	2
Tool kit - aircraft	1	60	3	3	180	9
Tool kit - corrosion	1	60	3	1	60	3
Towing arm	1	130	8	1	130	8
Water rig;engine replenish	1	30	2	1	30	2
Water rig;engine wash	1	245	15	1	245	15
Defrosting plant	1	250	25	1	250	25
Tyre inflation kit	1	25	1	1	25	1
Oxygen rig	1	500	25	1	500	25
Nitrogen rig	1	500	24	1	500	24
Wheel change ramps	1 set	30	2	1 set	30	2
Line pouch	1	10	1	3	30	3
Sub Total		2010	123		2280	143

ANNEX A

ARMING & WEAPON PREPARATION						
Hoist Type C	2	120	2	4	240	4
Hoist beam and brackets	2	45	1	4	90	2
Lift beam	1	17	1	2	34	2
Weapons trolley Mk.2	1	200	18	2	400	36
Slings: Bomb	2	4		4	8	
Drop tank	2	4	1	2	4	2
Rocket pod	2	4		2	4	
Ordnance Tool Kit	1	80	4	1	80	4
Ordnance Briefcase	1	15	1	1	15	1
Jig for missile assembly (est)	1	20	10	1	20	10
Test sets (per weapon type)	1	30	3	1	30	3
Sub Total		539	51		925	64
TOTAL ESSENTIAL GSE		2930	204		4347	295
List 2. Desirable Equipment						
Hydraulic servicing trolley	1	400	30	1	400	30
Jacking gear	1 set	780	21	1 set	780	21
Alternator oil rig	1	200	20	1	200	20
Engine tool kit	1	80	4	1	80	4
Sub Total		1540	75		1540	75
GRAND TOTAL		4470	279		5887	370

ANNEX B

EXAMPLE OF SMERSH OUTPUT (1)

```
                                                   RESTRICTED                                      29FEB80      PAGE    3

    ENQUIRY REF;  13999                   ENQUIRERS IDENTITY;   MR WELLS

    QUESTION;  ERS&PEGASUS-103&(E108+E911+E979+E930)*

    TITLE;  AERO-ENGINE REJECTION SUMMARY

*****************************************************************************************************************************
DATE OF EVENT'    ORN        ' REASON        ' A/C  ' ENGINE SERIAL NO  ' HRS NOR '  SYMPTOMS/FAILURE CAUSE
------------- ------------- ------------- ----- ----------------- ------- -------------------------------------------------
 SIGNAL DTG  '      STATION ' REJECT TYPE  ' MARK ' MODULE SERIAL NO  '  -REPR  '       OVERHAUL REPORT
             '              '              ' ---- ------------------ ' ------- '
             '              '              ' POSN '  RELEVANT MODS    '  -LIFE  '
*****************************************************************************************************************************
             '              '              '      '                   '         '

30SEP76      ' 38XV78330096 ' INV          ' HA   ' 8979              ' 432     '  VIBRATION ON RUNDOWN. (COUNTS 813). LP DAMAGE
 051540Z OCT '    WILDEN    '     BASIC    '  GR3 '                   '  N/A    '      DEFECT INVESTIGATION REPORT NO AM/D 5640
             '              '              '    0 '                   '   567   '      TURBINE SECOND STAGE HP BLADE & DISC BROKEN.
             '              '              '      '                   '         '      COMBUSTION CHAMBER TURBINE ENTRY DUCT BROKEN
             '              '              '      '                   '         '      .TURBINE AXIAL RUB.EXHAUST DUCT CRACKED.
             '              '              '      '                   '         '            FINAL CLASSIFICATION: BASIC
             '              '              '      '                   '         '

07FEB77      ' 65XZ13307027 ' INV          ' HA   ' 8930              ' 126     '  SEVERE VIBRATION ON CLOSING THROTTLE TO IDLE
 110940Z FEB '    WITTRG    '     BASIC    '  GR3 '                   '  126    '  AFTER MAXI PAD LANDING, SHUT DOWN, HP COMPRESSOR
             '              '              '    0 '                   '   300   '  DAMAGE, MARGINAL PW/RAFG/PEG/14(OIL PUMP GEAR)
             '              '              '      '                   '         '      DEFECT INVESTIGATION REPORT NO AM/D 5670,
             '              '              '      '                   '         '     .ENGINE SATISFACTORY CONDITION DURING TEST
             '              '              '      '                   '         '      RUN VIBRATION UNCONFIRMED.UNIDENTIFIED F.O.D
             '              '              '      '                   '         '      HP COMPRESSOR & TURBINE.
             '              '              '      '                   '         '            FINAL CLASSIFICATION: NON-BASIC
             '              '              '      '                   '         '

05SEP77      ' 46XW76424087 ' REPAIR       ' HA   ' 9108              ' 291     '  BIRDSTRIKE.(1803 COUNTS)EXCESSIVE DAMAGE TO 1ST
 051400Z SEP '    GUTSLO    '   NON-BASIC  '  GR3 '                   '  N/A    '  AND 2ND STAGE FANS
             '              '              '    0 '                   '   600   '      BIRD STRIKE.LP COMPRESSOR & HP COMPRESSOR
             '              '              '      '                   '         '      DAMAGED.EXHAUST DUCT CRACKED.RACEWAY ADAPTOR
             '              '              '      '                   '         '      B469672 LOOSE. TURBINE HP LINER CRACKED BULK
             '              '              '      '                   '         '      HEAD/RAY.COOLING PIPE BRACKET CRACKED
             '              '              '      '                   '         '            FINAL CLASSIFICATION: NON-BASIC
             '              '              '      '                   '         '
```

ANNEX B

EXAMPLE OF SMERSH OUTPUT (2)

```
[illegible] RAFC 6 FOR: STEVENS(10735)        ENQUIRY REFFRENCE : 54062

PEGASUS 103 REJECTIONS NOV78 - NOV79


[illegible] NO TAILNO ORN DATE  RFP STN WHENHOWFOUND  OPNL EFFECT    M/E SER NO  ME USE     SYMPTOM            DEFECT           ACTION TAKEN

   65  XW733  02/11/78  3SQN    OOP(LIFEX)     MAINT          8924            297  LIFE EX COMPONT   LIFE EX COMPONT    RPL ENG R/S
    8  [illegible] 08/11/78  GUTSLO  BEFORE FLGHT   MAINT          8922              5  RUBBING           NOT KNOWN          RPL ENG R/S
   65  XW669  17/11/78  4SQN    TURN ROUND     MAINT          8953            303  FOD-ORIG-UNKNOWN  DAMAGED            RPL ENG R/S
    3  XZ137  20/11/78  GUTSLO  OOP(LIFEX)     MAINT          8944            512  LIFE EX CONPONT   LIFE EX COMPONT    RPL ENG R/S
    3  XZ128  20/11/78  1SQN    AFTER FLIGHT   MAINT          9128            184  CONSUMPTION HIGH  CONSUMPTION HIGH   RPL ENG R/S
   92  XW924  21/11/78  GUTSLO  AFTER FLIGHT   MAINT          8903            455  CONSUMPTION HIGH  NOT KNOWN          RPL ENG R/S
   24  XV762  21/11/78  4SQN    FROM ADD LOG   MAINT          8936            420  MISSING           MISSING            RPL ENG R/S
   54  XV747  29/11/78  4SQN    OOP(LIFEX)     MAINT          9114            300  LIFE EX COMPONT   LIFE EX COMPONT    RPL ENG R/S
   71  XV747  04/12/78  GUTSLO  FROM LIM LOG   MAINT          8905            283  TEMP LOW          NOT KNOWN          RPL ENG R/S
   20  XW764  05/12/78  3SQN    PRIMARY *      MAINT          8932            319  FAILED TEST       NOT KNOWN          RPL ENG R/S
   38  XV762  11/12/78  BAEDUN  HOVER          MISSPTFAIL H   9108            489  WARNING LIGHT ON  NOT KNOWN          RPL ENG R/D
   23  XV751  12/12/78  GUTSLO  OTHER RECT     MAINT          1116            423  ENG OIL LEAK      WORN               RPL ENG R/D
   27  XV784  15/12/78  4SQN    CRUISE         NIL EFFECT     9001            177  IND SUSP/WRONG    NOT KNOWN          RPL ENG R/S
   61  XV756  17/12/78  4SQN    AFTER FLIGHT   MAINT          8955            527  DAMAGED           BLADE SCORED       RPL ENG R/S
   60  XV757  18/12/78  1SQN    STNY ON GRND   NIL EFFECT     8949            538  ENG OIL LEAK      ENG OIL LEAK       RPL ENG R/S
   58  XV759  18/12/78  233OCU  TAKE-OFF       MISPTFAILESD   8911            495  ENGINE BLOWBACK   DAMAGED            RPL ENG R/S
   33  XV761  05/01/79  GUTSLO  EN POWER CHK   MAINT          9116            423  FAILED TEST       NOT KNOWN          RPL ENG R/D
   20  XZ131  25/01/79  4SQN    AFTER FLIGHT   MAINT          8966            250  NICKED            BLADE DAMAGED      RPL ENG R/S
   52  XV778  26/01/79  WITTRG  GRND RUNNING   MAINT          8939            297  FAILS TO ROTATE   NOT KNOWN          RPL ENG R/S
    5  XW765  29/01/79  3SQN    AFTER FLIGHT   MAINT          8974            178  BENT              BENT               RPL ENG R/S
    4  XZ123  05/02/79  1SQN    SUPP SERV      MAINT          8906            380  MISSING           BOLT BROKEN        RPL ENG R/S
   23  XW269  08/02/79  GUTSLO  OOP(LIFEX)     MAINT          9119            537  LIFE EX COMPONT   LIFE EX COMPONT    RPL ENG R/D
   29  XV747  20/02/79  GUTSLO  OOP(LIFEX)     MAINT          8905            293  LIFE EX COMPONT   LIFE EX COMPONT    RPL ENG R/S
    1  XW925  23/02/79  1SQN    TURN ROUND     MAINT          8987            300  FOD-ORIG-UNKNOWN  FOD-ORIG-UNKNOWN   RPL ENG R/S
   18  XW271  26/02/79  233OCU  OOP(LIFEX)     MAINT          9022            297  LIFE EX SUB-UNIT  LIFE EX SUB-UNIT   RPL ENG R/S
   29  XV748  23/03/79  233OCU  OOP(LIFEX)     MAINT          8917            679  LIFE EX SUB-UNIT  LIFE EX SUB-UNIT   RPL ENG R/S
   15  XZ134  30/03/79  3SQN    TURN ROUND     MAINT          8943            131  NICKED            NOT KNOWN          RPL ENG R/S
   71  XV789  02/04/79  4SQN    OOP(LIFEX)     MAINT          9124            599  LIFE EX COMPONT   LIFE EX COMPONT    RPL ENG R/D
   70  XV753  04/04/79  233OCU  TURN ROUND     MAINT          8913            532  ENG OIL LEAK      NOT KNOWN          RPL ENG R/S
   79  XW765  18/04/79  3SQN    TURN ROUND     MAINT          8981            411  NICKED            NICKED             RPL ENG R/S
   25  XV779  30/04/79  GUTSLO  MAJOR   (1)    MAINT          9109            476  HOLED             BLADE LEAKING      RPL ENG R/S
   37  XV761  02/05/79  GUTSLO  OTHER RECT     MAINT          9028            531  DAMAGED           NUT OUT OF ADJ     RPL ENG R/S
    4  XW766  04/05/79  GUTSLO  GRND RUNNING   MAINT          9104            431  STICKING          NOT KNOWN          RPL ENG R/S
   23  XV790  08/05/79  GUTSLO  AFTER FLIGHT   MAINT          2250            208  WATER LEAK        WATER LEAK         RPL ENG R/D
   27  XV790  10/05/79  GUTSLO  GRND RUNNING   MAINT          8929            435  STICKING          NOT KNOWN          RPL ENG R/D
   49  XW269  14/05/79  GUTSLO  CRUISE         NIL EFFECT     9017            399  RPM GRND IDLE LO  OUT OF LIMITS      RPL ENG R/S
   57  XZ131  15/05/79  GUTSLO  TURN ROUND     MAINT          8926            315  TURB TIP GAP INC  TURB TIP GAP INC   RPL ENG R/S
   56  XZ130  23/05/79  1SQN    OOP(LIFEX)     MAINT          9018            605  LIFE EX SUB-UNIT  LIFE EX SUB-UNIT   RPL ENG R/S
   57  XW269  23/05/79  4SQN    FROM LIM LOG   MAINT          9017            398  OUT OF LIMITS     NOT KNOWN          RPL ENG R/S
   46  XV741  05/06/79  3SQN    FLT TEST IU    NIL EFFECT     8922            111  HI TIT/TOT/JPT    NOT KNOWN          RPL ENG R/S
   59  XV761  06/06/79  3SQN    AFTER FLIGHT   MAINT          8945            398  HI TIT/TGT/JPT    NOT KNOWN          RPL ENG R/D
   75  XV810  07/06/79  4SQN    FROM LIM LOG   MAINT          8994            300  RPM GRND IDLE LO  NOT KNOWN          RPL ENG R/S
   79  XW769  11/06/79  1SQN    OOP(LIFEX)     MAINT          9008            313  LIFE EX SUB-UNIT  LIFE EX SUB-UNIT   RPL ENG R/S
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RESTRICTED

THE EMPLOYMENT OF JET V-STOL AIRCRAFT AT SEA

PART 6

SHIP SPECIFICATION

'How are you getting on?' said the Cat as soon as there was mouth enough for it to speak with.

Alice waited til the eyes appeared, and then nodded 'Its no use speaking to it,' she thought, 'til its ears have come, or at least one of them.'

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INTRODUCTION

The object of this whole study is to examine ways and means of getting the Sea Harrier aircraft and its kind to sea in a sub-capital ship. Problems studied so far are the methods by which the aircraft could be launched, the numbers of aircraft in a flight to give a worthwhile and consistent availability, and the size of the supporting echelon that must accompany them. Now attention must be directed towards the factors determining the nature of the ship that would be suitable for carrying this package.

In attempting this it is intended to set aside the demands imposed by Command, Control and Communication, C^3, as belonging to a different province, while nevertheless appreciating that in setting up a force which is to be effective in operations, C^3 will be every bit as important as launch capability and logistics. Attention will be concentrated on the physical attributes the ship must display, particularly those concerning minimum size and performance.

Minimum is the watchword here, and it will be shown that there is a size of vessel below which operation would not be practicable. This size does not depend only on the dimensions of the deck required for takeoff and landing, the sea conditions in which the ship is intended to work are also a consideration, in some cases the predominant one. The effects of ship motion on the performance off a skijump need to be investigated, as do its effects on the aircraft suspension. In order to get a feel for this it is necessary to cover a brief introduction to the sciences of oceanography climatology and ship architecture.

The means of conducting an instrument approach and final landing will dictate the guidance equipment with which the ship is to be fitted. Development of this section of flight operations for aircraft of the Royal Navy is almost complete, and the techniques developed will be described in summary, with acknowledge to their originators.

Once the approach to deciding the ship dimensions has been charted, the range of types of ships available in reality or in theory can be scanned to see which ones have the potential to fulfil the need.

SUMMARY

The deck size for takeoff is determined by performance off a skijump launch, while the deck size for landing is decided by landing scatter. The arguments against a rolling landing show that a vertical landing is the only mode that need be considered.

The minimum flight deck length is not necessarily the minimum length of the ship. For operation in North Atlantic conditions consideration of the winter wave spectrum show that a length of at least 400 ft is necessary.

The worst pitching case of a ship this length means that the launch speed for a typical aircraft need be increased by only about half a dozen or so feet per second to allow for the downswing component and the reduction in effective skijump angle, while the worst effect of rolling is to impart a sideforce equivalent to about ⅓g on the undercarriage.

Of the range of types of surface vessels that could be considered for operations of aircraft of the Harrier type launching from a skijump, Hydrofoils and Hovercraft are eliminated on the grounds that the characteristics that make them attractive to the Navies of the world are not appropriate to this type of role, leaving only displacement vessels.

No suitable displacement vessel is in the inventory at present, so design and development work is going to have to be carried out before one becomes available. The case is aired for further investigation of the Arapaho Merchant Air Capable ship, the Small Waterplane Area Twin Hull ship and a possible development of the Type 22 Frigate.

THE SHIP REQUIREMENT

Harrier aircraft have flown from forty different warships of nine different Navies. It is worth noting that the smallest of these ships still displaced over 6000 tons, and worth noting too that the only non-helicopter aviation ships being built are of aircraft carrier shape and small aircraft carrier size, the Italian "Guiseppe Garibaldi" being about 12000 tons, and her Spanish counterpart, the successor to the 'Dedalo' being 15000 tons. Does this mean that Navies and shipbuilders see no place for VTO jet aircraft in a ship of a size normally only associated with one or two helicopters, or does it mean that the problem has not been considered in sufficient detail for them to realise that VTO jet aircraft could be effectively supported in a small ship and that they will always continue to opt for the biggest ship they can afford.

The arguments supporting the big ship are very strong and well established. There has always been a tendency for ships to get bigger, and this applies not only to warships but to merchant ships as well. For instance in the fifty years up to 1964 while the registered merchant tonnage in the United Kingdom increased by only 10% the actual number of ships represented went down by a factor of two-thirds (Ref.1). The capital cost per ton is less for a big ship than it is for a small one, a big ship requires proportionately fewer people to man her than does a small ship, (doubling the size of a tanker increases the numbers of the crew by only 10%), two forty-aircraft ships will cost more than one eighty-aircraft super-carrier, and as has been argued in Part 3 of this study the only way that the investment in an elaborate launching aid could be justified would be to have it in a big ship where it serves not one aircraft but several. So we see the development of the colossal nuclear powered fighting ship of the Nimitz class, costing $2,000,000,000 to build, but demonstrably cost-effective, at least in terms of all measures of operation in times of peace.

What then is the case to support the small ship? Some of the answers to this question will emerge when the Nimitz comes to the end of her days and the problem has to be faced of finding her successor. As far as the Royal Navy is concerned they lie in the knowledge that we are no longer in the business of buying big ones and must look elsewhere for the solution to our problems. One solution is to adopt a small-ship design to enable the operation of VTO aircraft. The smaller ship may not offer the best bargain in commercial terms, but a number of small ships can demonstrate qualities that one or two big ships, while admittedly possessing greater striking powers, cannot ever aspire to. The most telling ones are that they can be in more places at one time, so that putting one in dock for refit or modernisation does not halve the operational fleet, and that replacing them will not come as a single financial shock. Ships of medium size are already coming into service with the Royal Navy. The only flexibility we have lest to exercise can be in the variety of smaller ships we build.

There is a size below which a ship can be no more than self-supporting. If she has to support a payload, such as an airgroup, in addition to herself, she must grow. If that airgroup is to be enhanced by the addition of VTO jet aircraft, then either the ship will have to grow even further, or the original airgroup will have to step down and make way. What this means is that even if there were ships already in service to which we could deploy one or more Sea Harriers, these Harriers would not be just a source of added versatility. They would have to take the centre of the stage, they would be cuckoos in the nest, and like the cuckoo they would oust the original occupant and then demand all the care and attention the parent could offer. If a mixed airgroup were still called for it would need either a bigger ship or more ships to make it possible.

At present there is no small warship on the Royal Navy inventory with a flight deck large enough for a Sea Harrier to land on, so we have to set our sights elsewhere, to the extent of introducing a new design if we have to.

The task then is to establish the parameters for a Harrier-capable ship. It has already been shown that the Reliability and Maintainability characteristics of the Harrier-family indicate that the aircraft could form a viable airgroup with a minimum size of three, while operation of a singleton remains an option available for occasional use, as from a Forward Operating Base, rather than on a basis of regular establishment. Also, whatever aircraft should come along to succeed the Harrier, it is not likely to be markedly more Reliable and Maintainable or less Reliable and Maintainable than the present aircraft, and therefore these figures can confidently be read across to the next generation of aircraft. This leads in turn to the proposition that if the Sea Harrier should dictate the size of the ship that operates it, and if procuring a ship or ships of that size is going to stretch the available funds to the limit, then that ship will have to do for the Harrier successor, and that successor will have to be of the same sort of size as the Harrier is today.

Ship Size.

The first step in sizing the ship must be to review the considerations by which the size of the Flight Deck is determined. These of course depend on how the aircraft is to be launched and how it is to be recovered. Once the dimensions of the decks required for flying off and for landing on have been assessed the larger set of the two will decide the dimensions of the minimum ship.

Flying Off Deck

The aircraft can takeoff purely vertically or with a forward component of flight. No matter how attractive and impressive vertical takeoff is, and no matter how much the performance of the aircraft in this mode is improved, the fact will always remain that the payload will be bigger if it takes off horizontally than if it takes off vertically. Certainly as long as the aircraft continues to be powered by Vectored Thrust, (and there is no evidence that any other form of propulsion for VTO aircraft is being developed by either the Bristol end or the Derby end of Rolls-Royce), then the ballistic launch will remain the most effective form of takeoff.

Therefore a flying off deck will be necessary, and this will be complemented with a skijump. If performance off the skijump were the only criteria to be met then this should be built with an exit angle of 30^{o}. While undercarriage and aircraft configuration constraints remain to be borne in mind this angle can only be achieved with a structure which is disproportionately high, so 20^{o} is more realistic while current thinking sets the limit at 15^{o}.

For this angle, as shown in Part 3, the length of the skijump deck should be not less than 250 ft.

The width of the flying off deck need not be much more than the span of the aircraft. This is very modest compared with the runway width requirements for takeoff of a conventional fixed-wing aircraft. The reason is as follows. A conventional aircraft taking off will leave the deck with all its weight supported by its wings. As it accelerates the weight transfers more and more from wheels to wings and the effective contact between wheels and deck becomes less and less. If there is an element of crosswind present the aircraft will drift over the deck under its influence, while, in any event, nosewheel steering will become progressively less effective. An aircraft flying off a skijump however does so with only about one third of its weight supported by its wings, the remaining two thirds still hold the wheels in contact with the deck. The firmness of this contact is augmented by the rotational forces developed as the aircraft runs around the curve of the skijump itself, so nosewheel steering remains effective throughout the whole period of the launch, and so in consequence a narrower runway is seen to be adequate. So a takeoff is a positively controlled manoeuvre and the dimensions of the area required for its performance can be known and adhered to, in this case a deck about 270ft x 40ft will suffice. Landings, however, are different.

Landing Deck

When taking off the point of departure is known exactly When landing, however, the point of arrival is subject to variable influences from all manner of sources, so the space available for landing must be extended to accommodate these. Consider, for a start, a conventional rolling landing. In an approach at 3° an error in height of only half a foot means a difference in point of touchdown of 10 feet. If the approach is too fast by 5% the roll-out distance to dissipate this extra kinetic energy is increased by 10%. Provision must be allowed for lateral scatter as well as linear scatter, albeit not to the same degree. What this all implies is that the size of the area from which an aircraft may operate is set by the landing performance, not the performance at takeoff.

Rolling landings are not appropriate for aircraft of the Harrier family. This is rather a disappointment to those lured by the potential attraction of a slow rolling landing followed by a gentle braked stop as might be performed by a STOL aircraft borne on its wings throughout its entire flight regime, because such an approach does imply the possibility of landing at an all-up weight well above that at which a vertical landing can be achieved. Unfortunately the manufacturers calculations show (Ref.2) that a landing run of at least 600ft is necessary before the landing weight can be increased significantly above that at which a vertical landing can be made. Two of the reasons have already been suggested, viz the implications of touchdown scatter due to height error and roll out scatter due to speed and weight variations, but the others, being particularly apposite to the vectored-thrust aircraft, are worth setting out in full and studying. They are:

a. For the aircraft to be able to flare at touchdown there must be a margin of wing lift available for use. This means that the approach conditions will not have been the best one possible for the airspeed flown, and so the potential gain will already have been partly eroded.

b. The aircraft incidence at the point of flare is limited anyway by the layout and proportions of the undercarriage.

c. The influence of the jetwake on the airflow over the wings is such as to reduce the effective angle of attack, so that the degree of flare called for would be increased by a further amount still.

d. Without a flare the vertical impact velocity is higher than it would be on an ordinary vertical landing, so the undercarriage would suffer more.

e. Once on the deck the aircraft must still be controlled. The deceleration available from its brakes is much less than the acceleration available from its engine at takeoff, so the landing run is bound to be far longer than the takeoff run.

f. The only method of keeping the aircraft straight during this transition period on the deck would be nosewheel steering, and this militates against the use of a flare on landing, which is the essence of a successfully controlled arrival.

The only way to get round all these objections would be to reintroduce some sort of arrester gear. In an earlier part of this study when the prospect of catapult takeoff was under inspection, grudging consideration was given to the possibility of equipping the aircraft with gear for accelerated takeoff and it was admitted that this might be possible at the expense of a small amount of extra weight and a lot of development effort. The problems of fitting the aircraft out for arrested landing as well are in a different league of difficulty altogether. The challenge of arranging any form of arrester gear that could trap the aircraft efficiently wherever it should touch down within the area of scatter of its point of impact without posing the threat of damage to the outriggers is more than can reasonably be handled without changing the aircraft out of all recognition, while the idea of reintroducing arrester gear to a ship is in the same category as that of installing a catapult and must be rejected for the same reasons.

So the vectored-thrust aircraft will always be expected to land vertically, and the size of the area it needs for this will set the size of the landing platform for any ship in which it might serve.

Emergency Landing

Abandoning the idea of arrester gear leads to the question of how a landing could be handled in the event of a vertical landing being impossible for some reason. If this situation should arise, due to failure of the nozzles to obey a down selection, a failure in the hover control system, (both of which are extremely unlikely), then it can be assumed the aircraft will need to be recovered at a speed appropriate to wingborne flight, i.e. about 200 ft/sec. With a flight deck some 250 ft long, the mean deceleration necessary to bring the aircraft to rest is 2.48g. This load would have to be applied somehow to the surface of the aircraft which is nowhere stressed to cope with decelerative factors anywhere near this size, and the barrier would have to keep the aircraft within the confines of a flight deck not much wider than itself if it were to avoid damage by or to the structure of the ship. This presents a major challenge to the metal structure of the current Harrier and even more of a problem to the composite structure of one possible successor. In the fixed wing aircraft carrier the Safeland barrier could be justified because it formed a back-up system to the conventional mode of landing, but it is difficult to envisage justifying the cost of developing a barrier system for a Harrier-capable ship to be used only in the extremely unlikely event of such a non-standard approach to the deck being necessary

Risk of a Non-Standard Approach being necessary. The probability of an aircraft being incapable of carrying out a vertical landing due to an internal engineering failure has been stated to be extremely remote. The measure of this remoteness,essential to know for a full evaluation to be made, can be derived from data available from the Maintenance Data Centre at Swanton Morley.

These data show that for the reaction control and nozzle systems combined there have been 13 events is approximately 33,000 hours of flying that caused or could have caused hovering flight to be unachievable, 3 in the reaction control system and 10 in the nozzle mechanisms themselves. This points to a hazard rate of 1 in 2500 hours. This is adequately remote, but further analysis of these incidents shows it to be capable of being reduced to a figure which is even remoter still. Of these thirteen failures to operate, eleven were due to physical stiction or intercomponent fouling, one to FOD alone and only one to a computer malfunction. The eleven cases of fouling and stiction were all amenable to early detection and correction by adjustment, and show that clearances in some of the mechanisms are very tight and therefore suspectible to blockage by FOD.

The lesson put forward is that rigorous attention to detail when servicing and adjusting these systems, supported by meticulous avoidance of FOD could together reduce the incidence of inability to perform a vertical landing to negligible proportions.

Landing Deck Dimensions

The parameters from which the size of the landing deck may be calculated are the extreme dimensions of the aircraft, the values of scatter currently experienced and the rules set out in BR766A,

Aircraft dimensions	
Outrigger span	22 ft
Main wheel to tail	20 ft
Main wheel to nose	28 ft
Main plane span	25 ft

Scatter figures	
Airborne scatter	20 ft
Landing scatter	15 ft
Heading error	±20°

Landing circle diameter:- 23 ft
(The diameter of a circle enclosing the whole undercarriage and centred on the main wheels. It is the area on which the aircraft would be positioned following a perfect landing).

Wheel landing area diameter:- 53 ft
(Landing circle diameter + 2 x landing scatter)

Mainplane Swept Area

Area the mainplane could sweep during a landing and taking into account Airborne Scatter. When calculating the area it is assumed that the main wheels have taken up their extreme landing positions.

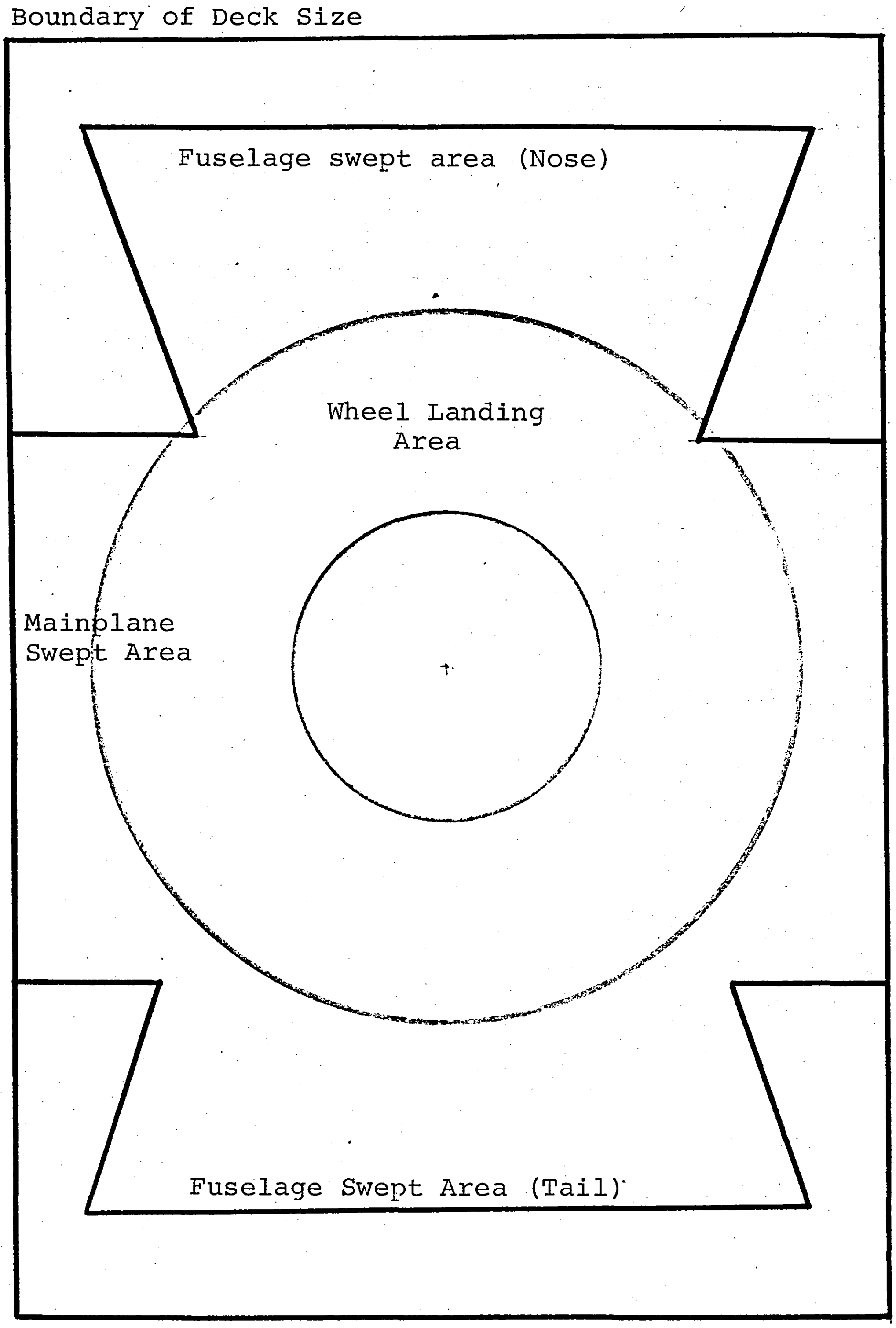
Fuselage Swept Area

Area swept by the extremities of the fuselage during a landing, taking account of heading error and airborne scatter.

The minimal landing area size resulting from all this measures 95ft x 65ft (Fig.1), but this is not necessarily absolute. The smallest deck the Harrier has landed on so far is that of RFA Green Rover, 85ft x 55ft, and other statements of the areas necessary are 17m x 22m (56ft x 72ft) (Ref.3) and a value of 75ft x 75ft offered as the size of the landing pad for the AV-8B (Ref.4).

Suitability of Ships in RN Service

For comparison with this landing area requirement derived above the following are the flight deck dimensions of current ships in service with the Royal Navy :-



Proportions of Landing Deck

FIGURE 1

		Length (ft)	Breadth (ft)
Warships	Type 42	59	33½
	Type 21	62	40
	Type 22	66	36½
	County	77	45
	Leander II	73½	36½
	Leander III	72	38
Fleet Auxiliaries	Forts	112	59½
	Old Rovers	99	51
	Tides	79	50
	Olwen etc	81	56
	Ness	115	53
	Regents	81	60½
	Repeat Rovers	85	51
Trials	Engadine	160½	58

It can be seen that no current sub-capital warship could offer a Sea Harrier any hospitality other than as a landing deck in an emergency. This is no great cause for concern however because it should be recalled that every member of every class listed has an aircraft and a role already assigned to it, and that to attempt to equip it with an aircraft of a totally different nature would bring about an imbalance somewhere else within the force.

The RFAS and the Engadine could land a Sea Harrier, and it follows that the larger ones could be considered for operating one, given the manpower and equipment listed in Part 5. This would have to be a short term operation however for all but the Regents, as they alone have a hangar wide enough to house the aircraft.

Deck Size - Summary

It appears then that the extreme dimensions of the minimal flight deck for Sea Harrier operations are 270 ft in length, (the largest dimension of the flying-off deck), by 65ft in beam, (the smaller dimension of the landing-on deck). The next question to look at is whether a ship of these dimensions would meet our needs. The answer depends on how much ship motion can be accepted in the theatres in which it is intended to operate, and that in turn depends on two things, the response of the ship to the influence of the sea, and the force of the sea to be endured.

SHIP RESPONSE

A ship at sea moves with six motions, three rotational and three translational. These are pitching, rolling and yawing about the rotational axes, and heaving, surging and swaying along those axes. The motions of greatest concern in flight deck operations are pitching and rolling.

Pitching

A ship has a natural period of pitch and this period depends on her loading and her dimensions. When moving through a regular sea she encounters wave crests at regular intervals called the Period of Encounter, and her resultant motion will be the combined effect of the tendency to move in the natural period, and to renew or increase the motion as each new impulse is received, i.e. to move in phase with the period of encounter, especially when this is greater than the natural period. For a given wave speed the period of encounter will shorten as the ship speed into a head sea increases, and will lengthen as she moves out of a following sea. Pitch motions will become really bad if the natural period of the ship and the period of encounter get to coincide and clearly this is a state to be avoided.

A guide to establishing the pitching period is:-

$T_p = 0.25\sqrt{L} - 0.35\sqrt{L}$; the coefficient increasing for ships whose main mass of machinery is at an extremity (Ref. 5); while the formula giving the natural period of a deep ocean wave in terms of its length from crest to crest is:-

$$T = 0.442\sqrt{\lambda} \qquad (\text{i.e. } \sqrt{2\pi\lambda/g}) \qquad (\text{Ref.5})$$

Thus a ship of length 270ft would have a period of between 4.1 secs and 5.75 secs, and the lengths of waves with which synchrony would be achieved would, from the formula above, be in the range 86ft to 169ft. This of course is for the case of a motionless ship head to sea. If the ship has forward speed then the period of encounter will reduce, i.e. a longer wave will tend towards synchrony, while this effect will be offset if the ship is travelling across the sea rather than straight into it.

If V is the speed of the ship in Knots, and λ the length of the sea wave then the period of encounter is given by

$$T = \frac{\lambda}{2.26\sqrt{\lambda} + 1.69V \cos A} \qquad (\text{Ref.6})$$

where A is the angle between the course of the ship and the direction of the waves.

Thus our 270ft ship travelling at 15 knots with a 250ft length wave 30° off the bow has a period of encounter of 4.3 secs, and the risk of synchrony is high. Waves of length 169ft to 250ft are characteristic of the sea states raised by winds running at speeds of up to 24 Knots (Ref.6, Fig.56), described as the Beaufort scale as Force 5-6 Fresh to Strong Breezes, and are typical of winter conditions in the North Atlantic. Clearly a length of 270ft is not the most felicitous one to which to design a Harrier capable ship if she is to operate anywhere in the Western Approaches.

This is borne out by experiments and experience reported in Ref.7., which asserts that the ship length can be set at 1.7 down to 1.1 times the average wave length for best pitch response, but should not be placed within 10% to 20% of the lower limit. Thus for the North Atlantic where the prevailing winter waves run in the range of 250ft to 400ft, unsatisfactory ship lengths will be 230ft to 360ft while good ship lengths will start at 460ft. This corresponds to a pitching period of about 5.4 to 7.5 sec, say 6.1 sec.

In general the larger the natural period of the ship and the greater the margins by which this exceeds the period of encounter, the more comfortable the ship will be. The risk of synchrony will be diminished, and the actual angle of pitch, which is a direct function of the ratio of the period of encounter to the natural pitching period, will reduce.

Rolling

The period of a ship in rolling or in pitching is governed by the ratio of the Radius of Gyration (K) to the square root of the Metacentric Height (GM), about the appropriate axis. The Metacentric Height for pitching is of an order far greater than that for rolling, to the extent that the ratio of their square roots always exceeds the ratio of the longitudinal radius of gyration to the radius of gyration in roll, and this leads to the result that the roll period is larger than the pitch period. In practice the natural period of pitching is usually between one third and two thirds that of roll.

The implications of this with regard to the motion of a ship in a seaway is that the period of encounter has to be relatively large for synchronous rolling to occur, and this will usually only happen in the case of an overtaking quarter sea, and can be avoided by a change of course.

In pitching motion the centre of buoyancy of the ship moves along a line fore and aft; there is no tendency for it to move off on a transverse axis and so pitching does not induce rolling. When the ship is rolling however, since the ship has no transverse plane of symmetry the centre of buoyancy moves not only athwartships but fore-and-aft as well, so induced rolling induces pitching also. It is therefore desirable that the roll period should never be a multiple of the pitch period, so that a harmonically coupled corkscrewing motion may be avoided.

Sea States

The size of the ship has been shown to be very much governed by the sea conditions in which she is expected to function, and we have seen, for instance, that 270feet is too short a length for a ship to avoid synchronous pitching in the waves drawn up by a Force 6 wind.(Note). What is important now is to find out whether such a wind and sea condition prevail often enough in the areas in which we wish to operate for it to be essential for our ship to be able to weather them in comfort, or whether we can get away with building the smaller ship and can accept that there will be periods during which she will be unable to operate in safety. We need to know what the frequency and seasonal distribution of these periods is likely to be in the sea areas in which we plan to exercise.

Data on Sea States is recorded in statistical form. It has already been shown in Parts 4 and 5 of this paper dealing with aircraft Availability, Support and Logistics that statistical summaries of information can sometimes mislead the unwary into forming wrong conclusions from the data presented, and that there is always value in reconstituting such condensed data if the means are available. If the means by which these data were collected and compiled is known we are better able to appreciate the information stored among them.

For example, the Sea State corresponding to a Beaufort Scale wind of Force 6 is Sea State 5. The introduction to the US Navy's Project NAVTOLAND (Ref.8) states that in the North Atlantic exceeds 5 for about 25% of the year overall, and for about 42% of the time during the worst quarter. This could be interpreted as precluding operation for one week in every four, or for one day in every four, and the only way to find out just what it does imply is to investigate where such figures come from.

Wave Height Recording

Waves on the surface of the open sea are a direct result of the wind blowing over it. For any wind speed there will be a certain height above which waves will not develop any further, and so for what is termed a fully-arisen sea there is a relationship between wind speed and wave height. If the global distribution of wind speeds is known, then the

[Note: The features of a Force 6 wind on land are: 'Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty'] distribution of wave heights for a fully arisen sea can be known too.

For any sea condition the heights of individual waves cover a wide spectrum. When assessing a sea state from observation of the wave height there is room for discretion and subjective judgement. One value that could be used would be the Average Wave Height. But in practice it is the larger waves that are more disruptive than the smaller waves and so a measure of just Average Height rather underestimates the condition. A better description is the average height of the largest one-third of the waves. This measure is called the Significant Wave Height, and it is about 1.6 times the Average Wave Height.

It has been found that when an observer is set the task of estimating the height of the waves by eye the figures he reports correspond very closely with the values of Significant Wave Heights as registered on a Wave Recorder (Ref.9). This lends more value to the selection of this particular parameter as an indication of sea conditions.

Sea State can be quoted as a single number in the same way as Wind Strength can be recorded using the Beaufort Scale. As a rough guide the Sea State of a fully arisen sea can be taken as being one less than the Beaufort Wind Force. Table 1, taken from Ref.10, shows a Wind and Sea Scale for a fully arisen sea driven by winds ranging from Fresh Breeze to Fresh Gale and lists the wind velocity, the Significant Wave Height and the Average Wave Length.

Meteorological observations are taken as a matter of routine by all the Ocean Weather Stations in the Atlantic. Since the end of World War II enough consistent data has been amassed for a definitive climatic Atlas (Ref.11) to be prepared, in which, month-by-month, the distribution of all the recorded measurements is set out.

Among the data displayed is a percentage breakdown of all Wind Force observations from Force 2 through Force 9. Accepting the Sea State to be one less than the Wind Force it is possible to produce a year-round record (and, therefore, forecast) of the probability of encountering a Sea State of a given value or less.

As an example, Table 2a and 2b show the monthly probability of encountering a Sea State of N or less, i.e. of being able to conduct flying operations if the ship can continue to operate in a maximum Sea State of N. The two locations for which the Table is compiled are Ocean Station India, at approximately 60°N, 20°W, some 200 miles due south of Iceland, and Ocean Station Romeo, 45°N, 18°W about 200 miles North West of Cape Finistere.

Sea State	Description	Beaufort Wind Force	Description	Velocity (kts)	Sig. Wave Height	Av. Wave Length
4	Moderate waves taking a more pronounced long form. Many white horses are formed (Chance of some spray).	5	Fresh Breeze	19	6.9	99
5	Large waves begin to form; the white foam crests are more extensive everywhere. (Probably some spray).	6	Strong Breeze	24	12	160
6	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind (spindrift begins to be seen)	7	Moderate Gale	30	22	250
7	Moderately high waves of greater length; edges of crests break into spindrift. The foam is blown in well-marked streaks along the direction of the wind. Spray affects visibility.	8	Fresh Gale	37	37	376

TABLE 1

Station I: Percent probability of not exceeding Sea State 4,5 or 6

	Month											
Sea State	Jan	Feb	Mar	Ap	May	Jun	Jy	Aug	Sep	Oct	Nov	Dec
4	47	50	49	47	71	79	82	90	65	61	59	45
5	69	68	70	72	94	94	96	98	82	83	78	72
6	82	85	87	89	99	99	99	99	90	94	89	88

TABLE 2a

Station R: Percent probability of not exceeding Sea State 4, 5 or 6

	Month											
Sea State	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec
4	66	63	75	71	78	91	92	85	86	76	61	63
5	84	80	88	87	89	98	99	95	93	88	79	79
6	96	94	96	97	98	100	100	99	97	96	94	92

TABLE 2b

Taking a simple interpretation these figures show that a ship-aircraft combination capable of sustained operations in Sea State 5 can stay in business about three-quarters of the time, i.e. 22 days out of 30 even during the winter on the Northern-most station, and for even longer if further South, while the ability to weather Sea State 6, with a significant wave height 5ft greater extends this capability to well over 80%. These conclusions could be refined even further if the data handled were the daily record rather than the monthly summaries, and the probabilities of not being able to operate for a number of days at a stretch could then be calculated. In fact the periods of bad weather probably occur in groups of four days at a time, the life cycle of a frontal depression. The necessary data is retained by the Oceanographic research institutes and could be accessed if necessary.

Thus, while the NAVTOLAND paper is generally correct in stating that a Sea State of 5 is exceeded for about 25% of the time throughout the year, a look at the sources of this figure taken month by month gives a much more useful set of information, and a finer breakdown still could be attempted if it were called for.

This section may be concluded then by the premis that while the minimum flight deck dimension should be 270 ft length and a maximum beam of about 65ft, if the ship is to operate in North Atlantic conditions with an acceptable degree of availability the length overall should be of the order of 460ft; certainly 270ft would be too short. This points to a displacement of about 6000 tons.

EFFECT OF FLIGHT DECK MOTION

Operating the aircraft from a pitching and rolling deck rather than from one that is steady brings in extra problems to do with undercarriage loads and takeoff performance. While detailed investigation of these problems will be the task of British Aerospace and the Ministry of Defence together for the next year or so while the initial trials of the Skijump launching system at sea are carried out and the results evaluated, it is worth taking an exploratory look at them here in order to obtain, some idea of how severe they might be.

The problems will lie in two areas:

a. Extra loads on the aircraft suspension due to ship motion in pitch and roll

b. Degradation or enhancement of skijump performance due to ship motion in pitch.

In the resolution of both of them the values already derived will continue to be used, i.e.

Flight deck length = 270 ft

Ship length = 460 ft

Ship period in pitch and, = 6.1 sec
arbitrarily assigned,
Ship period in roll = 10 sec.

Limiting pitch angle = $\pm 2^{\circ}$

Limiting roll angle = $\pm 5^{\circ}$

a. Extra loads on aircraft suspension

(i) Loads due to roll

An aircraft just about to leave the skijump while the ship is rolling will be subjected to two components of sideways acceleration:-

The linear result of rolling at a radius about a roll angle which is accelerating

and The coriolis acceleration due to rotation of its vertical component of velocity

Let Angle of roll = θ
Roll period = T
Vertical velocity = V
Max.roll angle = A
Radius from roll centre to deck = R

Assume Simple Harmonic Motion:-

$$\ddot{\theta} = -(\frac{2\pi}{T})^2 \theta$$

So linear acceleration at deck $= -(\frac{2\pi}{T})^2 \theta R$

Angular velocity $= \frac{2\pi}{T} \sqrt{A^2 - \theta^2}$

So Coriolis acceleration $= 2V \times \frac{2\pi}{T} \sqrt{A^2 - \theta^2}$

Total acceleration $= \frac{4\pi V}{T} \sqrt{A^2 - \theta^2} + (\frac{2\pi}{T})^2 \theta R$

By differentiation, this is at a maximum at

$$\theta = \pi RA / \sqrt{R^2\pi^2 + V^2T^2}$$

Using the data already assumed, plus:

R = 26ft (Height of 15° skijump + roll radius of 13ft)
V = 31ft/sec (Vertical component of 120ft/sec off 15°)

$\theta = 1.27^\circ$

and corresponding acceleration = 3.06 ft/sec
$\simeq$ 0.1 g

(ii) Loads due to pitch

Here we will assume the worst case, ie the skijump lip is right at the bows of the ship, so the pitching radius is half the length of the ship.

Using the same figures and calculations as for roll,

$\theta = 1.43^\circ$

and corresponding acceleration = 11.9 ft/sec
= 0.37g

This presents a strong case for having the skijump exit as near to the pitch centre as possible, so that the radial component is minimised.

If the skijump exit were coincident with the pitch centre, then the only acceleration remaining would be the coriolis component. The maximum value of this, at $\theta = 0^\circ$, would be: 8.3 ft/sec
= 0.26g

b. Variation in Skijump performance due to pitch

A take-off from a flat deck that is pitching means that the aircraft will become airborne with an error in its attitude and an added vertical component in its departure velocity. In the worst case the effects of downward slope and downward velocity combine to give a total change of flight path angle equal to two or even three times the half-amplitude of pitch. For example an aircraft launched from a flat deck that is pitching through ±1° can lose a total of 3° in its departure attitude. This shortcoming of angle of attack can only be compensated for by an increase in take-off speed. The increment to recover a 1° loss in pitch from a flat deck is 20 knots, and as the length of the takeoff run depends on $(\text{speed})^2$ this amount is very significant.

The problem with a skijump launch is not so marked. The variation in launch performance will be due to two factors, one being that the design angle of the skijump itself has been altered by an amount equal to the pitch angle, and the other being that the vertical component of velocity will be altered by an amount equal to the tangential speed of pitch. For our purposes it is accurate enough to consider them separately.

Alteration of skijump angle

A pitch range of ±2° means that a 15° skijump varies between 13° and 17°. Fig.2a shows how the end speed required to launch an aircraft with nozzle angle of 60° varies with launch weight for each of these angles. The trade off at these conditions is measured by the vertical separation between the two curves and is about 2 ft/sec per degree of pitch, or as measured by the horizontal separation, about 250 lb difference in launch weight per degree of pitch.

Effect of pitching speed

Fig.2b shows the way the launch speed for a hypothetical aircraft weighing 22000 lb and nozzle angle of 60° varies with vertical speed component. This will be at its maximum as the deck moves through the position of zero pitch, and its value will depend, for a given pitch range, on how far ahead of the pitching axis the departure point actually is. For a half-ship length of 230ft, a pitch cycle of ±2° and a period of 6.1 sec the maximum velocity is 8.3ft/sec, which, if it could be turned to advantage could save 12ft/sec off the required end speed. However it is far more likely that the operator would have to plan for the worst case, ie the aircraft leaving the deck just as it swings down past the horizontal, in which case the end speed would have to be raised by 12ft/sec or the launch weight reduced by a corresponding amount.

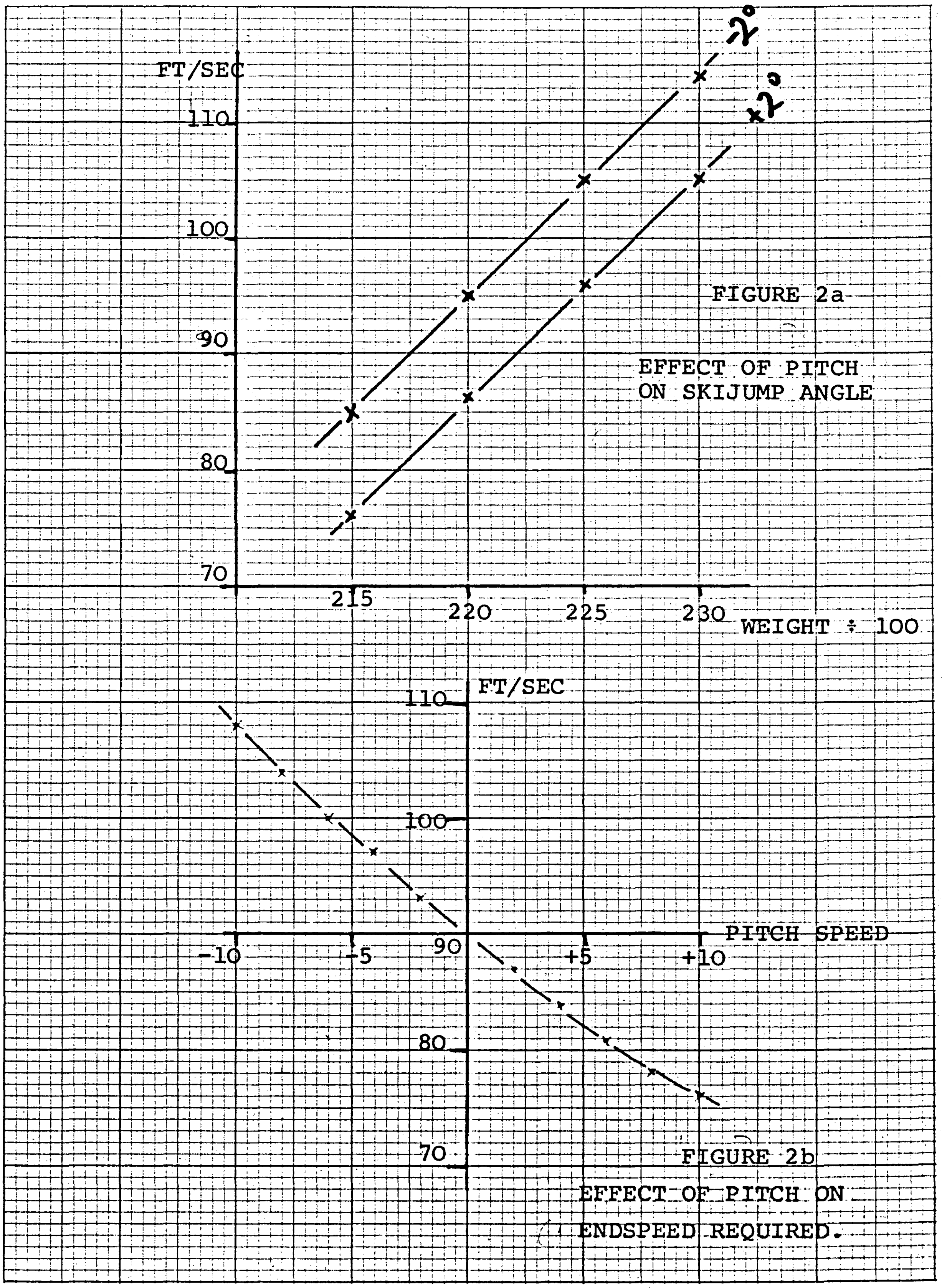


FIGURE 2a

EFFECT OF PITCH
ON SKIJUMP ANGLE

FIGURE 2b

EFFECT OF PITCH ON
ENDSPEED REQUIRED.

FIGURES 2a & 2b

Impact on landing

A final problem concerning the effect of ship motion on the structure of the aircraft concerns what happens when the aircraft lands on. It is the view of British Aerospace that to attempt to define the limiting amount of ship motions that will preclude an aircraft landing is well-nigh impossible, and the limiting Sea State accordingly cannot be designated. The ability to land on in conditions of considerable ship motion will depend on two influences:-

a. The additional loading on the undercarriage caused by increased impact velocities due to ship motion. From this aspect the limiting factor is considered likely to be the lateral velocity of the deck due to roll and sway producing increased sideforces at the moment of touchdown. (One implication of this is that it is possible for a big ship to reach its limiting condition before a small ship because of the greater total motion at the deck).

b. The safety of the aircraft on the moving deck after landing.

Landing itself is not too much of a problem compared with a helicopter in similar conditions. The helicopter has a large keel surface, a high centre of gravity and a low density, and a hauldown system is desirable in gliding it down onto the deck against all the influences trying to drift it away. The Harrier, like any fighter, is much more dense, and with its weight lower down its wheels will stay where they are put. But the relative position of its jets and its landing gear on which the lashing points are mounted preclude any move on the part of the ground crew to attach its tethers the moment power comes off, but the problem might arise of how to cover the brief period while the engine runs down and the aircraft is at the mercy of the deck. The suggestion that landing should be into a capture net is worth considering in this context if the problem should be seen to become a major one.

FURTHER FLIGHT DECK CONSIDERATIONS

There are a number of flight deck features which need to be considered regardless of the size of the flight deck or the nature of the vessel upon which it is mounted. These are introduced below.

Holdback

The case for fitting a holdback has already been aired in Part 3 of this Study. At the present time (August 1980) the question of whether to fit a holdback facility to the first skijump ships to come into service has not been resolved. If the decision to proceed with development of a holdback system is taken after all it will be remembered that the position of the holdback on the flight deck has to be able to be established anywhere along the axis of the takeoff run, otherwise there is a possibility of an aircraft reaching the curve of the skijump at a speed higher than that necessary for its weight and so running the risk of overloading the undercarriage.

Turntable

In order to wrest the longest run possible from a short deck takeoff the aircraft must be able to start its run from a position as far back along the deck as possible. If it starts up in the range and taxies aft preparatory to lining-up it needs to turn through an arc of about 150°. If the radius of this turn is large the aircraft will not have straightened up until there is a lot of deck behind it. The alternative, of making a very tight turn causes the outboard outrigger to scrub sideways across the deck. A possible solution to this problem, and one appropriate to a new-build ship, would be to install a turntable at the after end of the flight deck. In a small ship where the full extent of the available takeoff run was always to be used, the holdback could be incorporated in the same structure, and could be attached by the Flight Deck crew before the aircraft is rotated.

Markings

Nosewheel steering is expected to be effective throughout the whole takeoff run, but the pilot still needs a guideline to steer by. If a single centreline is marked out a pilot will set himself a target of perfect tracking and as a result will weave and tend towards overcontrolling. Perfect accuracy is not necessary in this case, so a better guideline is given by replacing the single centreline by a pair of tramlines between which the pilot should keep.

The recommended markings for a flight deck are described in Ref.12. A marked runway width of 38½ ft allows an aircraft to get as much as 3ft beyond the tramline and still have a clearance of 1ft between the outrigger and the edge of the deck, and with an extra margin to allow for wing tip clearances beyond any flight deck obstruction the total runway width adds up to 40ft.

Deck Strength

Flight decks in ships are very generously stressed and the ship constructor world asserts with some pride that they have never experienced a case where deck modifications have ever been called for.

The dishing which some flight deck structures exhibit, (the sort that allows puddles to form), is not a sign of flimsiness but is instead evidence of stress relieving by buckling, and is acceptable design practice. A degree of 1 in 50 is allowable.

In flight deck design, aircraft wheel loads are taken as being applied at a point rather than over a footprint, and the design criterion is that the aircraft will damage itself before it damages the ship.

Deck Surface Finish

The jet temperature from the rear nozzles of the Harrier is some 670°, and the nozzle temperature of some possible successors to the aircraft could well be much higher, especially if Plenum Chamber Burning is developed. Normal flight deck finishes can accept these temperatures up to a point, but it is unreasonable to expect the area of the deck which bears the brunt of all vertical takeoffs and all landings to stand up to them repeatedly.

It is the aim of the Admiralty Materials test establishment that flight deck coatings should last as long as the refit period of the ship and they are developing their finishes to meet this goal. The materials currently in favour are an elastomeric, XT 7825, and LAMREX, while the United States Navy strongly favours the use of the surface finish developed for use on the Jet Blast Deflectors for the F14, which is an electric arc sprayed aluminium coating (Ref.13).

RECOVERING TO LAND ON

The Problem

The tasks of bringing a conventional fixed-wing Naval aircraft through conditions of poor visibility and a low cloudbase to a safe deck landing and of bringing a deflected jet aircraft to a vertical landing through similar conditions differ so much that it is by no means adequate to design the technique for the new simply by extrapolations from the old. To understand why this is so, and why a totally new approach and landing procedure is having to be developed for the vertically landing aircraft it is necessary first of all to describe the final stages of approach and landing for the conventional fixed-wing aircraft and so appreciate the qualities of the aircraft that make it possible.

A controlled descent to the deck is carried out in two main stages. First the aircraft makes a fast descent to a height above sea level of about 1800 or 2000ft and levels out. The aircraft then reduces to its speed for final descent, and the pilot lowers wheels and hook and deploys the aircrafts high lift devices. Thus a level deceleration is carried out, and all configuration changes are planned to be complete by a mile or so before the path of the aircraft intersects the glide slope of the final approach. At this intersection, power is reduced and a steady and straight descent is established. Somewhere along this descent path the aircraft breakes out of the cloudbase, (if it had not already done so before), but this makes no difference to the pilots technique which continues to be to maintain his descent until he picks up the beam of the projector or mirror sight which guides him down to the deck. There is no attempt at a flared landing as the after end of the flight deck is crossed, and power is not reduced until a wire has been engaged and the aircraft brought to a full stop.

This performance cannot be duplicated by an aircraft which relies for part of its lift on vectored thrust. First, accurate controlled flight on instruments while partially jetborne makes too large a demand on the pilot, largely because, unlike its conventional counterpart, the deflected jet aircraft has no reserves of pitch stability, either natural or enhanced on which to draw. This puts decelerating and lowering of flaps and wheels in instrument flight conditions out of the question. Then the aircraft has no hook, and so its deceleration to a condition of zero speed relative to the ship must be done in-flight. This must be done in visual conditions, and achievement of a smart and positive deceleration which brings the aircraft to a hover right over the part of the flight deck on which it is to land cannot be accomplished by visual judgement alone.

When closing a ship on a run into a deck landing there suddenly comes a point, at a range of about three ship's lengths when depth perception all at once becomes effective. The ship is seen as an object in three dimensions in space, its image fills the windscreen, it gets closer very rapidly, the round down disappears from view and the landing is complete. This final telescoping of visual experience is all very well when the pilot can see a clear path for an overshoot if something goes wrong, but it is far from acceptable if the overshoot area is barred by superstructure, and the final deceleration must come not from the ship but from the aircraft itself. The pilot's approach to the deck will be nothing like as confident, and so for non-arrested aircraft, helicopters and Harriers alike, the technique has been to run into a position which is offset from the landing area, so keeping a clear path visible ahead, to establish a hover in formation with the ship, and then to sidle in to a hover over the point of touchdown.

For an aircraft like the Harrier, this latter part of the final approach can be dangerous if not handled correctly. The main source of possible error is that the pilot can be tempted to view his speed as being relative to the ship rather than relative to the airflow around his aircraft. Thus he might be tempted to sideslip the aircraft into position over the flight deck using rudder as the main control to effect the transition.

At speeds below about 50 knots, and certainly at the wind-over-deck speeds considered here, the aircraft is directionally unstable. The destabilising moment from intake momentum drag is more powerful than the stabilising weathercock effect of the fin and rudder, and the aircraft will yaw away from the wind. The dihedral effect of the wing sweep will cause this yaw to be accompanied by a rolling moment which will develop at a rate greater than the pilot can counter. The rolling moment is a function of sideslip and $(\text{airspeed})^2$ combined, and is therefore not too much of a problem at low forward speeds. The danger of this roll becoming uncontrollable can most likely arise when a pilot feels that the forward speed he has is low when in fact it is 20 or 30 knots and this is what can happen when in the hover and keeping station on a ship.

While in the current Harrier the pilot would receive warning from his Head-Up Display sideforce indicators and rudder pedal shakers before the situation got out of hand, it is much better that this situation should not be allowed to arise. It is better too for neatness of approach and for avoidance of trailing the jet efflux over more of the ship than is absolutely necessary, if the aircraft can make its approach directly over the counter of the ship without having to establish an intermediate hover alongside the ship on the way.

For this to be done, the pilot must be given confidence that the rate of deceleration he sets up while closing the ship will be just right to bring him to a stop over the touchdown point without causing him to sense a risk of overshooting Provision of the deceleration cue to give him this confidence is one aim of the approach package currently being developed for Sea Harrier use by the Flight Systems and Radio Navigation divisions at the Royal Aircraft Establishment, Bedford.

Systems under development

There are two agencies in the West engaged in meeting the challenge of how to guide a VTOL aircraft from the cruise to the hover through a arange of adverse conditions of weather and sea. One is the United States Naval Air Systems Command, the other is RAE Bedford.

Naval Air Systems Command have set themselves the target of developing a combined ship and aircraft system for effecting a fully automated transition to hovering flight in conditions of zero cloudbase, 700ft horizontal visibility and Sea State 5 (Ref.8). The NAVTOLAND (Navy Vertical Take-off and Landing Capability Development) is proceeding on a massive scale and is not intended to result in functioning hardware before 1995.

The problem set to RAE Bedford was one needing a much more immediate solution. With the Sea Harrier close to coming into service and no bad weather approach aid available at all, the RAE set aside the idea of a system directed towards the goal of guiding the pilot through the whole approach, the terminal hover and the landing, all without visual reference, on the grounds that it would call for an enormously complex system that would offer little more return than a simpler one whose goal was more realistic and less ambitious (Ref.14).

So they set a target to develop a system which would allow instrument flight to a state from which the pilot could take a visual and instrument cue to start his deceleration establish his hover, and complete his landing by visual references supported by optical aids. This meant that a cloudbase at zero feet was not acceptable so instead the limiting cloudbase was set at 200ft, with visibility of ½ mile (Conditions in the Atlantic and off N.E.Iceland are at 200/½ or worse for 16% of the year, compared with the NAVTOLAND target which is exceeded about 6% of the time. These percentage figures could of course be resolved more finely if required). This condition is more demanding than is likely to be encountered in practice. In reality a static cloudbase of 200ft is most unlikely - if the cloudbase is at 200ft it is because it is going up or the cloud is broken, and similarly, a visibility reading of less than 1000 metres is technically, fog. This is acknowledged by RAE who observe that if they can meet these requirements then the system will surely be effective in less extreme conditions.

The RAE Bedford System

Airspeed. For the Harrier the minimum airspeed for flight on instruments without a stability augmentation system is 120 knots. Use of the stability augmentation system fitted permits this speed to be reduced to 100 knots, but as the system offers no redundancy, single failure protection requires the minimum to be maintained at 120 knots.

In zero wind it takes just ½ mile to decelerate from 120 knots down to the hover. So if the pilot flying level at 120 knots and 200 ft is given the right cue at ½ mile from the ship, he can initiate his deceleration with every confidence that he will not overshoot the deck.

Descent to 200ft. There are three paths by which an aircraft in or above cloud could be directed to the point at 200 ft and ½ mile from which it begins its deceleration to the hover. It could approach by:

a. A straight-in path on a line of constant slope.

b. A steep descent to the cloudbase followed by a more shallow approach to the ship.

c. A descent to the cloudbase, a period of level flight until the glidepath is met, then the decelerating descent (Fig.3).

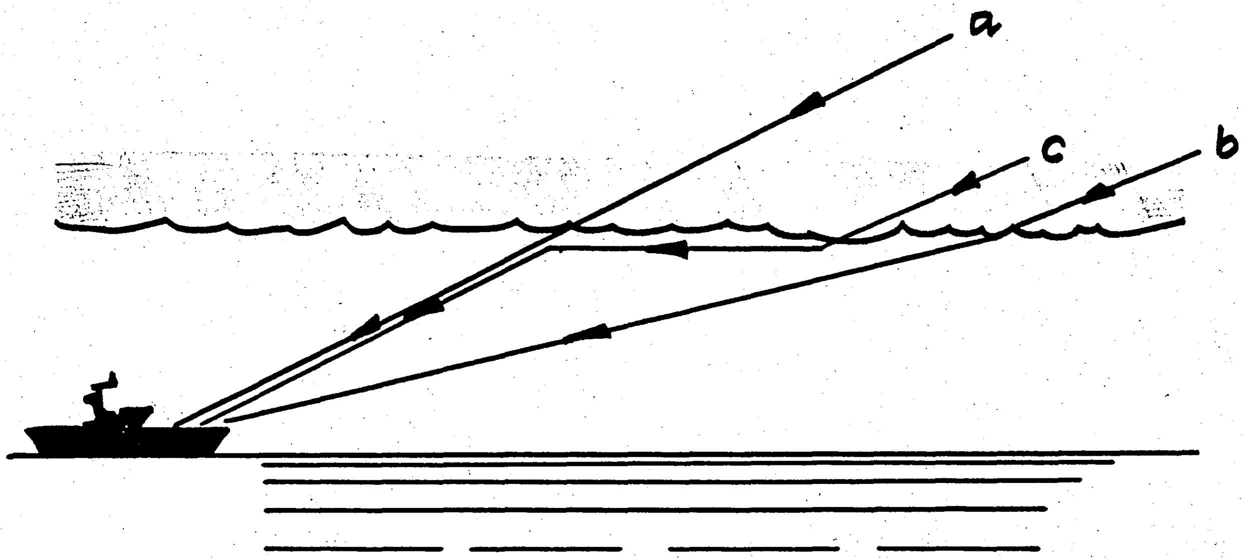


FIGURE 3

Of these, the first two share the disadvantage that the point at which the aircraft breaks cloud will coincide only rarely with the extended glideslope. If the aircraft breaks cloud too close to the ship the approach is spoiled, while if it breaks cloud too far away, or following the second type of approach the pilot has the ill-defined task of making a step adjustment in his rate of descent, and the final leg of the approach will be started only imprecisely.

The third type of approach on the other hand permits the pilot to settle down in straight and level flight for a while 'to allow the needles to stop swinging around', and the next step, the initiation of the reduction to the hover, can be started from a flight condition which has been established with confidence.

Path C is the descent chosen, and by setting the nozzles to the Hover Stop at the ½ mile point, the pilot knows his aircraft will have virtually stopped by the time the visual cues he gets from the ship are strong enough to rely on. The whole profile is shown in Fig.4.

When the skijump was introduced, the term 'Runway in the Sky' was coined to describe how a surface function had become translated into an airborne one. When describing the deceleration lane from the ½ mile point to the edge of the deck, the term is equally fitting.

Radar Guidance

Guidance for the sectors of the homing and approach which are flown totally blind comes from a MADGE (Microwave Aircraft Digital Guidance Equipment) installation. In its shorebased form this is a two-man portable approach and landing aid which responds to interrogation from an aircraft by returning signals which can be interpreted as information of azimuth, elevation and range. This can be displayed on an ILS flight director but in the Sea Harrier it will appear on a modified Head-Up Display. MADGE will be fitted to all the British aircraft carriers and is suitable for fitting to all air-capable ships.

Visual Aids - 1.The ½ mile cue

Once close to the ship the pilot can adjust his flight path in response to visual cues extra to his own visual judgement. There are two such aids already established and proven in service, and they are both candidates for consideration for this purpose. They are the Projector Sight and the Helicopter G.P.I.

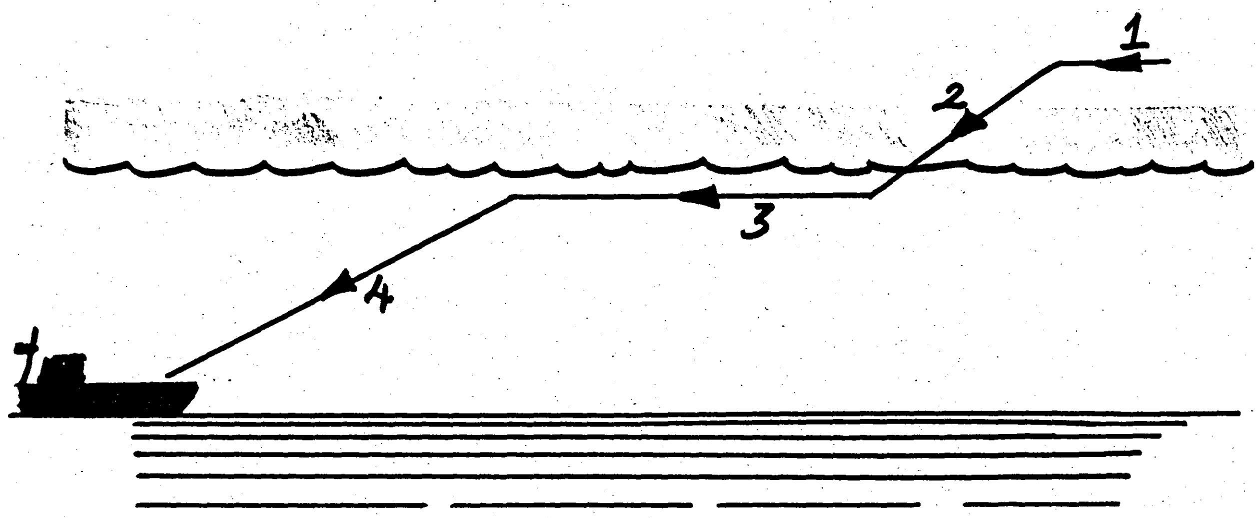
The projector sight was rejected initially because there is no suitable location in HMS Invincible where it could be installed. It was also considered to be unnecessarily demanding on pilot performance, (rather like a single centre-line to follow on a takeoff run), because any indication other than spot on is regarded as unacceptable, which might have been so for a Phantom approaching at a closing speed of 100 knots, but is not so for the Sea Harrier whose closing speed dwindles to zero and for which a broader band indication is all that is necessary at the outer limits of the range.

The 3-sector GPI, for its part, is not stabilised, and its colour discrimination is not good enough to be relied upon at a distance and in poor visibility.

Instead, the RAE have developed HAPI - Harrier Approach Path Indicator.

HAPI is a stabilised system of two projectors, axially separated along the ship by a distance, initially, of 300ft.

RAE BEDFORD: APPROACH AND LANDING PROFILE



Segment		Speed (k)	Jet Angle	Rate of Descent	Gate	Remarks
Join:	1	170-120	$0^o - 65^o$	0	Centre-line	
Descent:	2	120	65^o	500	Lineup	Slope Guidance
Level:	3	120	65^o	0	160'-200'	Visual Contact
Decelerate:	4	120-0	HoverStop (& speed Trim)	A/R	Hover 40'	Overshoot at 0.35 mi. if necessary

FIGURE 4

Each unit projects a beam viewed as one of two colours with a very sharp cutoff between them depending on the position of the observer.

Each shows Red in the lower sector and White in the upper, and the aftermost one is set at a marginally shallower angle than the foremost one. An aircraft approaching from astern sees two reds initially, and as he intersects the cutoff of the nearer beam it appears to switch from Red to White. As he intersects the next one, it changes colour in the same sense. The first one gives the pilot a warning to prepare to descent, while the second one gives the ½ mile hover-stop cue to an aircraft at 200ft for the descent to begin. Following developments currently in hand, equivalent indications will also appear on the Head-Up Display.

2. Close-up guidance

Mounted above the forward HAPI, which, relatively, is a medium-long range aid, is a further one called a CAI-Close Approach Indicator. This gives a similar indication for close range but does so with more emphasis. The White (high) and Red (low) sectors extend 0.75° above and below the datum angle as steady lights, and outside those boundaries they are seen to flash.

The final position cue for the hover itself has not been decided. It will most probably be a horizontal array of lights disposed in the plane of the pilot's eye-level at the correct hover height in such a way that errors above or below that plane are immediately identified from the nature of the disruption to the pattern seen.

Approach Monitoring

All approaches can be monitored by a Landing Signals Officer. He has before him two presentations of the aircraft as it makes its approach. One is a stabilised and collimated Head-Up sight through which he observes the approach itself, while the other is a numerical display fed from the MADGE unit giving him aircraft Range, Height and Speed together with measures of the current error from the basic conditions.

Accuracy and Confidence

The system has been proved at RAE Bedford by intensive trials in the simulator using pilots with a very wide range of Harrier experience, and also at sea in HMS 'Hermes' in 1978.

The results for the system as a pilot-interpreted aid are:

Window at ½ mile point: Height error: ±26ft; lateral error ±144

Cooper Harper rating:	Untrained pilots (simulator)	4-5
	Trained pilots	3

THE CHOICE OF VESSEL

The principal attributes required of a vessel able to operate a flight of Sea Harrier or equivalent aircraft and to take advantage of the improved launch weight capability conferred by the skijump are that it should be able to mount a flight deck at least 270ft long, and that it should be seaworthy in conditions up to and including Sea State 5, which for a displacement ship implies a length comfortably greater than 400ft. Additionally of course it should possess a range and endurance to fit its operational requirement and must be able to generate at least 15 knots of wind over the deck.

There exists a wide variety of types of surface vessel that could meet this specification, available either off the shelf or after development of an existing design. It covers hydrofoils, surface effect ships, displacement surface ships and semi-submerged surface ships.

Of these the first two classes exhibit what at first sight appears to be an extra star quality, their dramatically high speed, while the remainder are limited to the more pedestrian rates of the conventional surface fleet. This quality has singled out hydrofoils and hovercraft for special attention, particularly by the United States Navy in its quest for a surface unit that can outship the fastest submerged nuclear submarine, but is high speed an attribute of any value to the future STOVL-capable ship?

A military aircraft flying from a ship is just a link in the transmission line by which an explosive store is delivered to an enemy. The store is carried by the ship first of all, then at a particular point it is transferred to the aircraft, and that carries it to another point after which it is released to make the rest of its way on its own. The lengths of these stages relative to the whole journey depend on the relationships between the speeds and the ranges of each vehicle, the ship, the aircraft and the store itself. Sometimes the aircraft leg can be left out altogether, sometimes we need only the ship, sometimes the store can make the whole journey by itself.

This one, two or three phase system of weapon delivery has characterised the development of all components of offensive warfare right from the time the first spear thrower found he could give his weapon a greater range if he threw it from a run. If the weapon's range is limited then the delivery vehicle must be swift to move so that it can bring it to bear with a minimum of delay, hence the need for speed in an Anti Submarine vessel using depth-charges or a short range ahead-thrown weapon. But once the speed and local range of the weapon are of an order greater than that of the ship, then speed in the ship is of lesser importance. Its value lies only in the promptness with which it can get its weapon to its war location. Once it is there is can be virtually stationary, leaving all the dashing around to be done by its aircraft and missile combination. A counter-argument, of course, certainly as far as use of the skijump is concerned, is that like the spear thrower the launching vehicle can use its own speed to impart greater performance to its projectile. This is certainly so for a ship launching an aircraft from a skijump, but once the speed of the relative wind had got beyond 35 knots or so, deck operations would become unmanageable, and this total wind speed is within the capability of the displacement ship to achieve and sustain.

That being so, the conclusion must surely be that the increase of 20 knots or more that a surface skimmer can show over a surface ship is not relevant to the needs of an aircraft which can close its target ten times as fast.

The speed of these craft is of more value in areas of close combat such as anti-submarine warfare and troop landing and support and it is unlikely that a case could be made for use of one as a STOVL-dedicated ship. They could of course provide a platform for an aircraft operating purely in the vertical takeoff mode, and so for this reason and for completeness of the record the hydrofoil and the surface-effect ship will be examined along with the displacement ship.

The Hydrofoil

The typical hydrofoil boat in civilian or military service today is about 100ft long, weighs about 100 tons, and needs about 5000 SHP to propel it at its maximum speed of about 50 knots. While it is foilborne, its performance obeys rules similar to those governing an aircraft in flight. The foils support it, like the airfoils supporting an aircraft, operate at a maximum value of Lift/Drag ratio of about 20:1, which means that the force driving it is about 5% of its weight.

When starting off, the power required rises steeply with the speed, and while hullborne exceeds that which would be necessary for a displacement craft of the same weight, because of the extra resistance of the hydrofoils and their supports. Once takeoff is achieved, with the hull clear of the surface and the water friction drag and wavemaking resistance largely eliminated, the main component of resistance is the induced drag due to lift, which is sensibly constant. The power then increases linearly with speed, plus a component for wind resistance, which will be considerable at high speeds into a head wind.

The foil loading, analogous to wing loading, will be very high compared with aircraft values of the order of 1000 lb/sq.ft. and its value follows the normal rules of scaling. In this lies the road to finding the hydrofoil's limitations. In an aircraft, if the weight is to be increased at the design stage, it is usual to increase the wing area in proportion, with the object of keeping the wing loading unaltered. With a hydrofoil, though, an increase in the foil area can have the effect of increasing the drag in the hull-borne condition to such an extent that the craft is unable to reach its takeoff speed. The alternative is to leave the foil area unchanged and derive the extra lift by operating at a higher speed. This will increase the takeoff speed and also mean that the foil loading will increase.

The speed through the water reaches its limit by 50 knots, at which speed cavitation begins to occur over the upper surface of the lifting foils, and the onset of this is accelerated by increased foil loadings. Cavitation is caused by sudden and violent implosion of voids in the lifting fluid as it goes from areas of low pressure over the lifting surface back to normal pressure further back,and can damage a foil in the same way as a ships propeller, and at a cost of a heavy loss of propulsive efficiency. It is feasible to get around the problem by designing a 'super-cavitating' foil over which cavitation is deliberately induced prematurely with the result that the implosive effect happens behind the foil. This restores performance at high speeds, making speeds of up to 80 knots attainable in theory, but means that cavitation is a problem at low speeds. The result of all this is that in hydrofoil terms, a vessel of 300 tons is regarded as being large.

The Royal Navy has one hydrofoil in service at present. HMS 'Speedy' is a modified Boeing PCH-1, is 116ft long, weighs 100 tons and is propelled by 7600 horsepower. The largest hydrofoils in service anywhere are the Russian Babochka (Grandmother) class which are 48ft longer, four and a half times as heavy, and with 3 x 15000 SHP gas turbine to propel them, need six times the power. It is clear that a power/weight ratio of 100:1 will offer neither economy nor endurance.

The largest hydrofoil yet schemed is the Grunman HYD-2, projected in 1974 for the US Navy. This would weigh 2400 tons and its power would come from 2 x 43000 SHP gas turbines for foil-borne use, plus a 5000 HP gas turbine for use when floating on its hull. Even on this craft the total deck area at 320ft by 50ft is barely large enough to accomodate a skijump.

The Hovercraft

A principal virtue of the hovercraft is its ability to beach itself. This is where its major attraction lies in the eyes of the Naval service, but it is an attribute which offers nothing to the Harrier operator. Its other virtues of minimal water surface contact which gives it immunity from torpedo damage and harm from contact mines, and its high speed, are, like the Hydrofoil, achieved at the cost of a large power requirement.

An empirical formula for the relationship between the weight of a hovercraft and the installed power necessary to support and propel it is:

$$\text{Horsepower} = 165(\text{Weight in Tons})^{\frac{7}{8}} \qquad \text{(Ref.15)}$$

This also gives a power:weight ratio of about 100:1 for weights in the region of 100 tons.

The largest hovercraft in UK service is the SRN Super 4 which weighs 300 tons, is 185ft long and has an endurance of only 5 hours.

The most ambitious schemes so far are, like the hydrofoil projects planned initially for the US Navy. In 1975 both Bell's and ROHR engineering presented plans for hovercraft weighing 2000 tons, measuring approximately 250ft by 100ft and having a top speed of 80 knots. Power for these would have come from six General Electric LM-2500 engines of 20,000 HP apiece, two for the lift fans and four for the water jet propulsion, which is the feature that would make them suitable for aviation use. In 1976, ROHR engineering received a contract to develop an ocean-going hovercraft of 3000 tons. This would have used three LM-2500 engines to power the lift fans alone.

All these projects were among the first victims of economy cuts made by the current US Administration, and none is proceeding any further at present.

The Hydrofoil and the Hovercraft together represent the only means of breaking out of the confines of the 30 knot limitation imposed by the basic physics of the displacement ship. This speed limit can be doubled without the power required going up by a factor of eight, but this will only be effective in roles where the demand is for a high speed dash of short duration. This does not describe the skijump Harrier operation, so both these types must be rules out on grounds of size, economy, endurance and inappropriateness.

The Displacement Ship

There is nothing to touch a conventional displacement ship for efficiency when it is travelling at its design speed. While the 2000 ton hovercraft needs no fewer than six LM-2500 engines to propel it, the 7600 ton DD 963 class destroyer is propelled by four and the 15000 ton Spanish aircraft carrier now being built can sustain 25 knots with only two.

The drag of a ship at design speed is only about 1% of its displacement, (Cf the Drag/Lift ratio of the Hydrofoil which is 5%), and while it increases rapidly above a speed/length ratio of about 1.1, the speed offered at this figure of V/ L = 1.1, V being in knots and L in feet, is still acceptably high. The increase of this speed, which is the speed for minimum wavemaking resistance, with length, is a further point to strengthen the case for a larger ship.

There are no small or medium sized warships in the current inventory which might be considered suitable for operating the Sea Harrier and its descendants in the manner considered in this paper, so some measure of innovation will be necessary to produce the ship required. The options are:

1. To adapt a ship of another class altogether

2. To design a totally new ship with an adequately large and stable flight deck area

3. To modify an existing design.

These options are illustrated by the following projects:

1. The US Navy's ARAPAHO plan for operating military aircraft off a merchant container hull.

2. The Small Waterplane Area Twin Hull (SWATH) ship.

3. The US Navy's 'Spruance' air capable ship (currently in abeyance), and the Harrier capable frigate based on the Type 22.

Each will be considered in turn.

The ARAPAHO Project

The ARAPAHO project, (which takes its name from an undistinguished tribe of Algonkian plains Indians), is one by which merchant ships could carry their own defensive aircraft in times of war. Its particular application at present is to the preparation of plans and hardware to permit the embarkation of a flight of SH-53 anti-submarine helicopters in a specially adapted Euroliner containership. It has a first cousin in what is called the SKU plan, SKU standing for 'subsidised keel-up' by which merchant ships would be designed and constructed in such a way that they can be converted into Navy combatant vessels within 24 hours.

The United States Navy is very aware that, in spite of the vast increase in airlift facilities made available by the development of ever larger transport aircraft, 95% of the military equipment required to reinforce the European theatre is still intended to go by sea, and that the merchant ships carrying it are going to need protection, especially against submarine attack. The Navy is aware too that it possesses only half the protective capacity it needs, and that the cost of assigning versatile conventional warships to the task of merchant ship protection would be prohibitive. The answer to this dilemma is to fit the merchant ships out to protect themselves.

It is not practicable to arm merchant ships in peacetime. A telling reason is that, once armed, a merchantman would forgo its status as a non-combatant and would find many of the ports of the world closed to it. So a means has to be devised so that the conversion could be carried out very rapidly when the time comes, and preferably at a regular port of call. This is where the Container ship presents itself as a suitable candidate for the job.

Containers are made in sizes whose dimensions and fittings are established world-wide by the International Standards Organisation. An ISO container will measure 8ft x 8ft in section, (so that it may pass through a railway tunnel) and 10, 20, 30 and 40ft in length. The fittings at each corner are standardised so that containers may be stacked on top of one another without the distortion of the whole structure exceeding set limits, e.g. the eccentricity in a stack six-high is limited to 1" laterally and 1.5" longitudinally.

Container ships are plentiful, in fact one third of the dry cargo in transit in the world is transported this way, and the proportion is increasing. All trading nations have built or adapted container ports to handle them. Thus a containership needs no cranes, booms or similar standing rigging.

The ARAPAHO proposal is to design an entire air facility with all its components ISO-compatible and fully containerised. When it is needed, the whole conversion kit can be carried by road or rail to the container terminal, there to be fitted to the ship designated, using the facilities of that port. While it would certainly be too optimistic to expect an Arapaho outfit to slot neatly into any containership of the right size chosen at random, it is reasonable to assume that the whole package could be designed to suit at least one particular class of ship and all the members in it.

Employment of a container ship permits the characteristics of economy of scale in big ships to be exploited once again. The larger the size of the host ship, the less will be the impact of the conversion on her primary task, and, of course, the better her seakeeping qualities will be. It is reckoned that an Arapaho outfit need take up no more than 15% of the cargo capacity (Ref.16), so that an adapted cargo ship can still carry 85% of her intended load. Carrying their own airgroups for anti-submarine protection would also mean that the larger container ships would be spared the embarrassing consequences of having to slow down so that their escorts can keep up with them. In World War II the speed of the average merchant ship in a convoy was 12 knots while her escorts fussed and fretted around her at 33; now the modern Euroliner cruises along at 28 knots while her escorts would be hard pressed to sustain 25.

A complete trial Arapaho installation is currently in course of assembly at the US Naval Air Engineering Centre at Lakehurst, New Jersey. Its purpose is to support the operation of four SH-3 helicopters for a total of 390 flying hours spread over 15 days, operating for the present at any rate, in VMC conditions only. The installation is required to have a life in and out of storage of 20 years, it has to be transportable by road and rail, it must be ISO-compatible and capable of being mounted within 24 hours, and it is planned to be ready for fitting trials before the end of 1981.

While the Arapaho can be thought of as being an expedient method of getting an escort carrier on the cheap, there is nothing hasty or makeshift about its composition. When complete it will consist of four major elements, which are the Flight Deck, the Accommodation Array, the Hangar Array, and the Fuel System Storage and Service Array. A brief summary of these modules is as follows.

The Flight Deck consists of open gratings surrounded by an ISO-compatible structural frame. It measures 200ft by 65ft, is illuminated for night operation and has space enough for two helicopters in a fully-spread condition. The Hangar is big enough to house four aircraft with blades folded and contains Workshops, Flying Control, and all associated offices and briefing rooms, while the fully ventilated Accommodation array provides berths and domestic services for 65 persons. The Fuel Farm holds 15000 gallons of JP-5 plus 10,000 gallons of Diesel fuel for the two 250 KVA Diesel generators which are also part of the package. The whole installation is dependent upon its host ship only for fresh water and firemans services, otherwise the function of the merchant ship is undisturbed.

The object of the fitting trials and the trials underway is to gain confidence that the designed ISO-compatibility really will work in practice, that the installation can be transported to the port of embarkation and assembled there successfully, and to record and analyse any unforseen difficulties that may arise in operation while actually at sea. In the view of the Royal Navys Constructor branch, one difficulty that very probably will be encountered will be that of deck and hangar distortion due to relative flexing between the container stack and the ship itself.

The amount of money allocated to the Arapaho project is $10,000,000, and this can be taken as being roughly what a complete kit might be expected to cost. If the price of a skijump were added to this, the result would be the first estimate of the cost of acquiring a Sea Harrier deck. The requirement for a modular skijump able to be containerised for storage and transportation can be filled perfectly by the components of the Fairey Medium Girder Bridge.

The Medium Girder Bridge

The MGB is a lightweight bridging system developed by Fairey Engineering Limited for the British Army as a replacement for the older steel bridges previously in service. A bridge is assembled from components made of Aluminium alloy, the heaviest fabrications are light enough to need only six men to carry them, and all the others weigh 450lb or less and need four men to handle them at most.

The units of a single storey bridge are 6ft long and form a roadway 13ft2in wide. They are joined to one another by simple pins. If a length of bridge 100ft - 150ft long is joined up on the ground and then raised at one end with no other support, the shape it takes up is eminently suitable for the profile of a skijump. The curvature is the resultant of the elastic deformation of the assembly as a girder, which accounts for 80%, and of freeplay between the individual panel units comprising it, giving the other 20%.

This was the principle of the skijump assembled and demonstrated at the Farnborough Air Show 1978 and at the Paris Salon 1979. A track of roadway, 126ft long, was built of two parallel sections of bridge, which with specially-built outriggers gave a width of runway of 38ft. Raising one end of this by 19ft resulted in a skijump shape with an exit angle of 15° (Ref.17). It is important to realise that a clean lift of one end is all that is needed to produce the correct curvature, no further rigging surveying or adjustment are necessary, and intermediate supports are put there only to withstand the extra loads as the aircraft passes over them.

The actual skijump MGB used at the Paris Salon is now in the hands of the US Marine Corps who intend to develop it as a moveable land-based takeoff aid as a component of what they term an Expeditionary Airfield. It has been shown to be readily portable, is easily put together in less than two hours, and the bridge section itself weighs only 30 tons.

So a Medium Girder Bridge assembly could readily be used to provide a launching deck for a container ship to complement an airgroup installation of the Arapaho type (Fig.5). If the Royal Navy were to find it operationally essential to get more Harriers to sea but lacked the deck space in the Fleet in which to embark them, then spill over

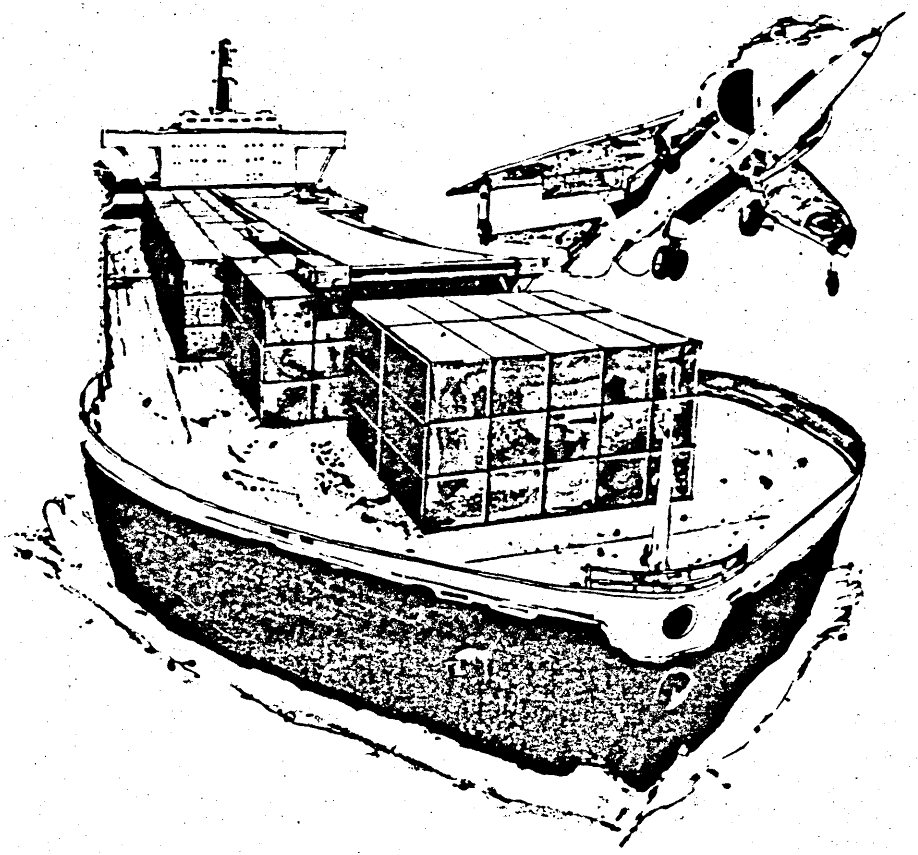


FIGURE 5

THE ARAPAHO SKIJUMP HARRIER

to a civilian ship would be the only answer. There are over twenty British Container ships with lengths between 400ft and 950ft, and plenty more suitable for coastal work in the 300ft to 400ft range.

Unless for some reason the forthcoming trials by the US Navy of a prototype Arapaho installation should come to grief completely, the idea of recruiting a container ship as an auxiliary aircraft carrier should be kept firmly in mind.

The Small Waterplane Area Twin Hull Ship

Two of the more extreme innovatory shapes for a future fleet, the Hydrofoil and the Hovercraft, have been considered as potential VTOL carriers and discarded. Their principal selling point, that of exceptionally high speed for a surface ship, has been shown to be inappropriate for the role of Harrier carrier. The third one on the drawing board however does not boast high speed but offers instead an extremely stable deck of a relatively large area on a ship of comparatively small size. These characteristics fit it particularly well for the role of small ocean-going air-capable escort ship, and would make it most suitable for adaptation to the Sea Harrier mission if ever it came to be built. This one is the SWATH.

The layout of the catamaran is well known. By sharing its load between two well-spaced hulls it offers much greater stability in roll than does a single hull of similar displacement, the cost of this benefit being an increase in wetted area, and therefore resistance to motion through the water of about 30%. But it is still prone to follow the motion of surface waves.

If however, the two hulls are totally submerged, with the deck and superstructure supported above the surface, this motion can be almost totally eliminated. This is the arrangement of the SWATH. The system for propulsion and fuel are located in the submerged hulls, and these hulls between them support an operating deck and bridge structure with its base clear of the wave crests. As the ship passes through a wave the only shift in buoyancy will be that due to an increase or decrease in the volume of supporting structure that is submerged, and because of the relatively small waterplane area of these sections this will be very small compared with the buoyancy of the whole vessel, so that if the two hulls are deep enough, stability in all but the heaviest seas will be excellent. In this way a ship could be built to the requirement of the smallest flight deck without suffering the instability that a surface ship of that length would display.

The United States Navy has been considering the advantages of a SWATH ship for a number of years. A first prototype vessel, the USS "Kaimalino" of 200 tons displacement is already built and under evaluation, and schemes exist on paper to project the design up to a ship of 30,000 tons (Fig.6). No new and unproven engineering principles are invoked, and the only problem area forseen is that of containing the bending moments at the junction of flight deck and supporting structure.

They see a ship of 3000 tons being adequate for operating three or four anti-submarine helicopters, the attraction of this size being that it is considered the biggest that could be built to be expendable in wartime (Ref.18). Such a ship could operate a similar number of VTOL aircraft off a skijump of up to 300ft, with all the extra benefits that would bring with it.

They envisage such a ship with its two hulls, two support sections, flight deck and bridge/island superstructure as being capable of being put together from subassemblies built in second division shipyards, and so amenable to volume production. The design is very tolerant of additions and deletions of topside weight without any risk of loss of stability, and its unitised design offers an attractive promise of being readily updated and refitted.

With a predicted ability to maintain 20 knots in Sea State 6, a STOVL-equipped SWATH would be a very attractive proposition, especially to a nation venturing into maritime organic air for the first time.

The Conventional Displacement Ship - Type 22 Conversion

The air capable version of the Spruance class destroyer has already been introduced in Part 3 of this study. At present the design is not progressing beyond the idea stage. The Spurance design is by British Standards a fairly big ship at 9500 tons and carries a large airgroup of upwards of a dozen aircraft. A more modest venture, carrying an airgroup of the size already considered, is a frigate conversion proposed by Yarrow Shipbuilders.

The Yarrow design (Fig.7) has been produced in cooperation with British Aerospace who advised the architects on the relevant aviation aspects such as flight deck and hangar size and aircraft dimensions. In adapting the original Type 22 Frigate arrangement it is intended to retain the original weapon systems (with the exception of a possible reduction in the Exocet installation) and provide the added aviation facility by widening and extending the ship which would now be longer by about 30ft and heavier by about 1500 tons.

The complement of aircraft is intended to be three Harriers plus two Lynx or one Sea King, or, alternatively, a maximum of five Sea Kings. Accommodation for these is made available by raising the Flight Deck to become in

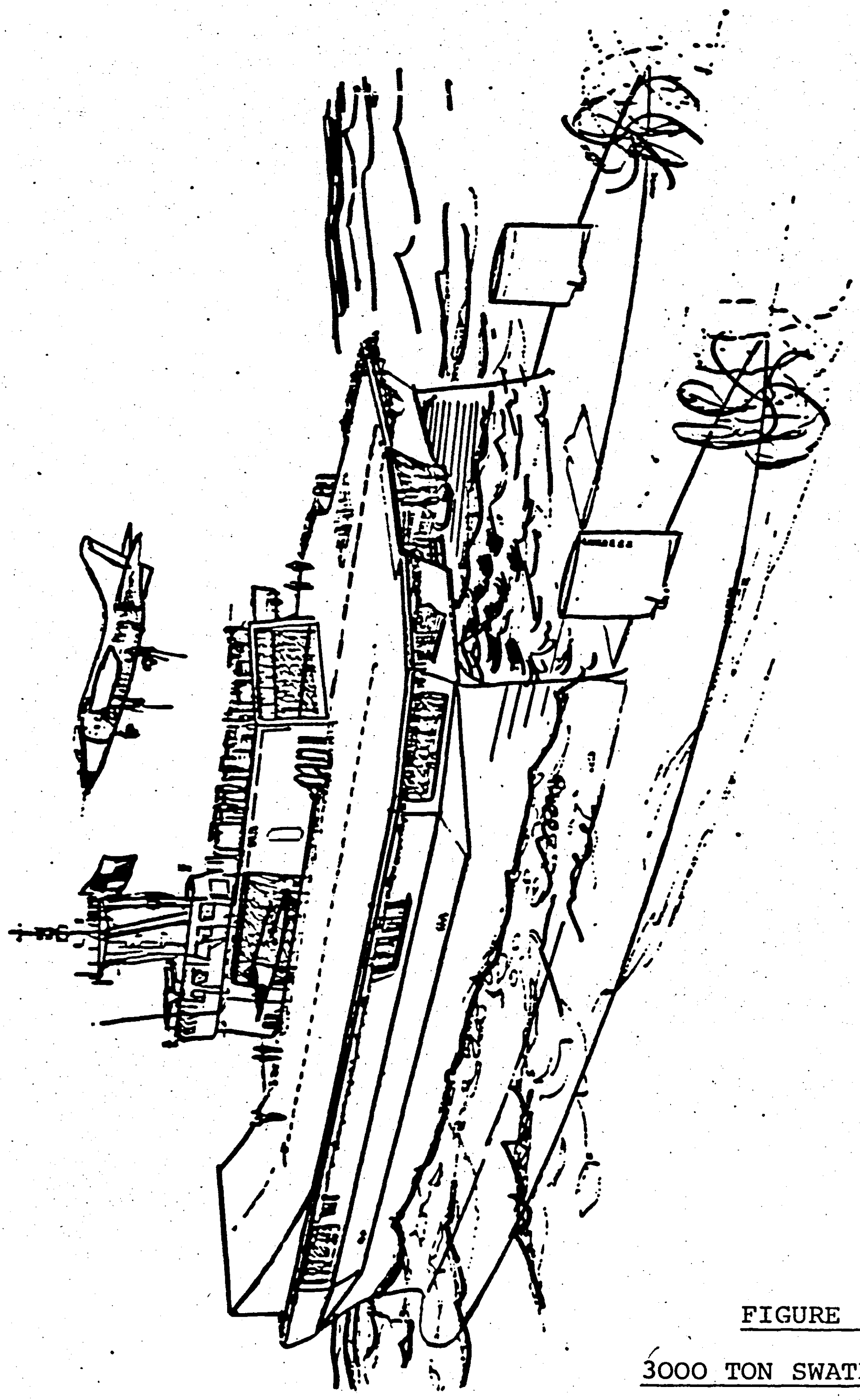


FIGURE 6

3000 TON SWATH FRIGATE

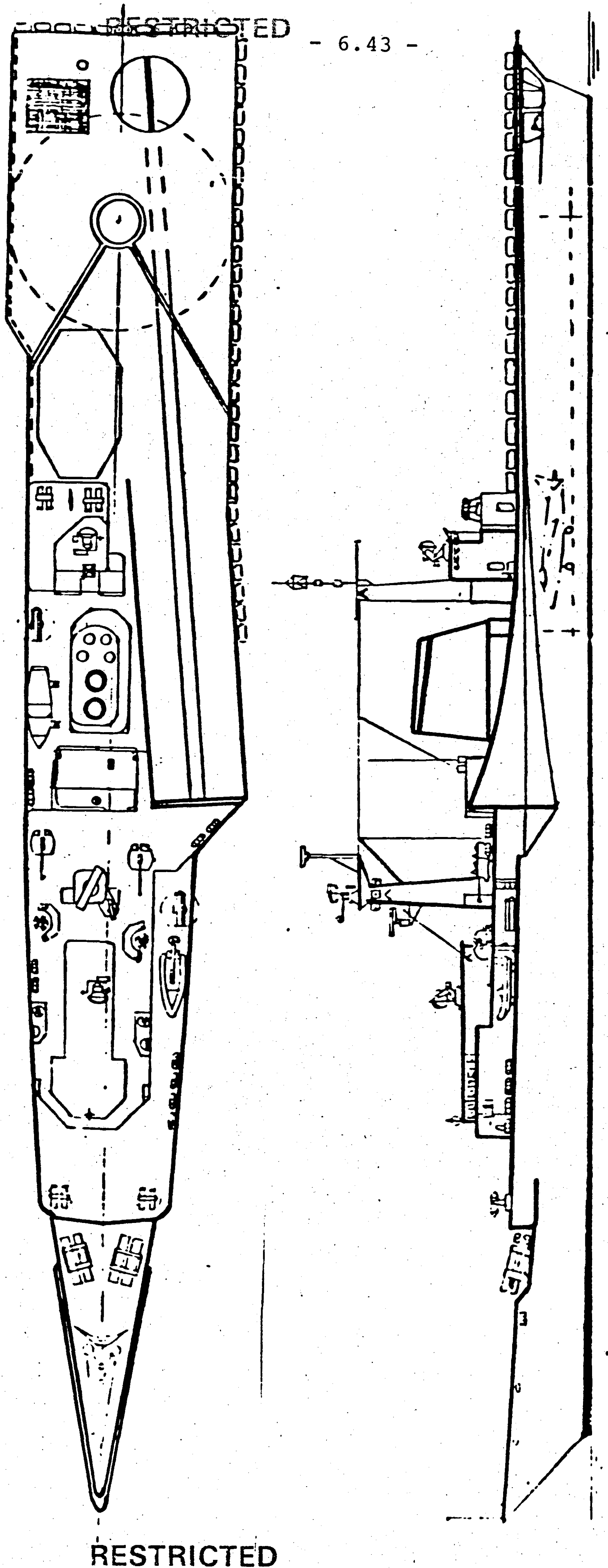


FIGURE 7

TYPE 22 FRIGATE VARIANT

effect a continuation of the one above, thus creating a hangar extended to the length of the ship. Increase of hull width above the waterline will allow space for two 'big-wing' Harriers to pass one another side by side. Hangar and flight deck are linked by means of a lift. This is supported by a system of three jacks, two against the side of the ship and the third, inboard, one, below the level of the hangar deck, so that with the lift in the down position movement on and off it would not be impeded. Moving the aircraft around the hangar in any sort of a seaway would be expected to present a problem. Yarrow intend to solve this by installing a system of rails on which aircraft movements would be controlled positively. The engineering challenge this presents is new but not insurmountable.

The flight deck measures 145ft by 72ft, with the available takeoff run being about 250ft, these dimensions having been recommended by British Aerospace, (and conforming with those derived independently in this paper). At the after end of the flight deck there is a turntable so that the maximum takeoff run can be made available

The launching deck ends in a 15^{o} skijump. This is little more than halfway along the ship's length, and therefore it is close to the pitching centre. This means that the detrimental effect of a downward pitching motion on the outcome of a launch would be only that due to the effect of losing one degree or more off the skijump angle, the downwards velocity having only little influence. The ship is stabilised in roll, and Yarrows expect continuous operation in Sea State 5 to be possible.

Provision for accommodation, stores, fuel etc to support the airgroup meet the requirements given in British Aerospace Paper HSA-KOA-N-HAR 170, Provisioning of a ship for a Sea Harrier Air Group, (Ref.6 to Part 5), and has been updated following discussion with this Author and study of the advance draft of Part 5 itself.

In this modified Type 22, Yarrows consider that they have a design for a fully viable self contained air capable ship founded on a proven and successful ship that is well established in service. At this stage the plan is still in outline form and could readily be amended to fit any customers particular needs, and it is to be hoped that customers will be forthcoming for this design which is visually very pleasing and deserves to succeed.

AVOIDANCE OF FOREIGN OBJECT DAMAGE

In the preceding part of this paper, a case was preferred for dispensing with an engine change facility when compiling the spares and support required for a Sea Harrier detachment to a sub-capital ship. This was based on the argument that the probability of suffering a catastrophic engine failure in circumstances likely to leave the aircraft marooned on the deck was low enough for the risk of not catering for it was acceptable. Also the case for dispensing with any provision for landing other than vertically is founded on a very low forecast probability of nozzle seizure. Neither of these cases would stand if they were not supported by a positive and vigorous campaign to eliminate any possibility of engine or airframe malfunction being due to damage by any foreign object.

The FOD problem that a Harrier can cause is in a totally different league from that due to any conventional aircraft with a similar performance. A Sea Harrier in the hover will be dispensing a total of 30,000 horsepower in downward thrust, at 800mph through the front jets, at 1200 mph through the rear jets and at 1700 mph through the reaction control jets (Ref.19). Where these jets meet the deck they do not merely rebound, instead they spread out radially in the horizontal plane, dispersing their energy by entraining ambient air, and forming jet sheets. Where two jet sheets meet the only way they can go is upwards, forming an energetic rising sheet.

If the aircraft is low enough for the flow from each nozzle to retain its own unmixed identity when it hits the deck, then a pattern of rising sheets will form, one in a plane running fore and aft, and the other across the span. The jets from the front nozzles are cooler and denser than those from the back, and having a greater kinetic energy they tend to dominate. This causes the spanwise sheet to tilt backwards, and as the aircraft descends the point where they meet moves forwards, (Fig.8).

Loose objects caught in the jet field can be set in motion in two ways. The radial speed of the jet sheet is of the order of hundreds of miles per hour and objects it encounters will be accelerated very rapidly indeed. If they are at all irregular in shape they will bounce, with every risk of entering the engine intake. Other items once they reach the interface between two jet sheets will be subjected to a local stagnation pressure underneath them strong enough to accelerate them vertically and project them into the rising air flow.

The high pressure on the surface of the deck can easily find its way under flat objects on that deck and lift them up if the pressure difference is high enough. It needs only ½psi to lift a 1" thickness of steel, and even a manhole cover can easily be thrown into the air in this way. This implies that on board ship, many items which might normally be considered to be too heavy to be a possible FOD hazard will be moved by the passage of a Sea Harrier over them, and will be dislodged upwards, not just outwards.

Suction from the intakes does not cause as big a problem as may be expected. It will not lift objects by

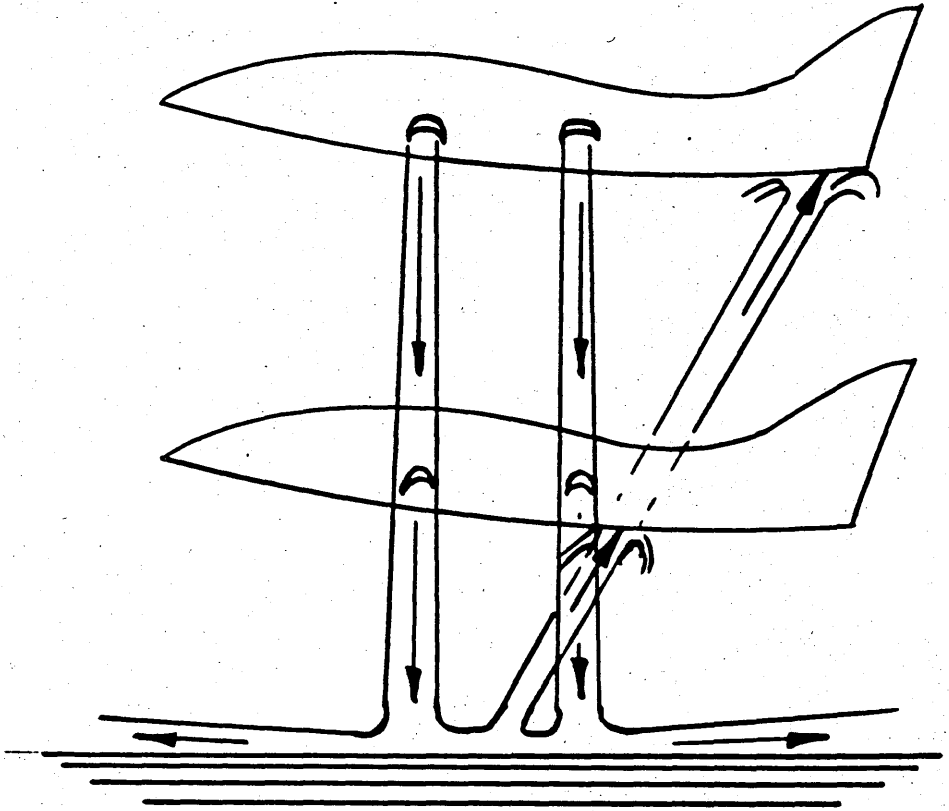


FIGURE 8

FORWARD MOVEMENT OF POINT OF IMPACT OF RISING JET SHEET AS AIRCRAFT DESCENDS itself except in particular conditions where a combination of engine speed, wind-over-deck and nozzle angle causes a vortex to form. The intake area itself however is a nest of potential FOD traps, the slow-in intake doors, the BL doors, the cabin conditioning system cooling air ducts and the cockpit access footsteps all providing little niches where debris may gather.

A particular area for FOD hazards in ships will be found in deck-edge walkways, catwalks and sponsons. These, especially the channel-sectioned ones, can form thrust-reverser buckets when an aircraft flies over them, and jet wash along a catwalk can dislodge anything not securely attached including lockers and refuelling hoses.

Whenever Sea Harriers are operated on detachments it will have to be made very clear to everybody involved, air group and ship's staff alike, that the penalty for a FOD-damaged engine or nozzle mechanism will be the loss of utility of the whole aircraft for as long as the detachment lasts.

CONCLUSIONS

The following summarises the conclusions that have been reached regarding the skijump air-capable ship.

Deck Size

The deck for takeoff needs to be 250ft or more long and 40ft wide, while the landing area should be about 85ft by 55ft. Vertical landings will be the only type performed.

The landing requirement can be met only by ships of the Royal Fleet Auxiliary and HMS Engadine, so these ships could be used for vertical operation only, for example as forward operating bases or emergency landing platforms.

Ship Size

For the ship to display a good year-round all-weather capability her length should be 400ft or more so that the response to a sea of Strength 5 is moderate and manageable.

Effect on Aircraft

The undercarriage of the aircraft will suffer extra loading from motion in pitch and roll, and motion in pitch will detract from the skijump performance to a small extent. If the skijump exit is not far from the pitch centre this defraction will be minimised.

Types of Ship

Hydrofoil ships and hovercraft are very unlikely to be developed to the size required for skijump operations.

Their extreme power requirements and short endurances militate against their qualification for the skijump role, while the high speeds of which they are capable are not necessarily an advantage.

The most suitable vessels are displacement ships, and their slower conventional speeds are adequate. There are no ships in RN service with the dimensions necessary for ski-jump operations other than dedicated aircraft carriers. The choices open are to mount a skijump on a merchant hull, to build a Small Waterplane Area Twin Hull ship, (which could get away with being no greater in length than its flight deck), or to adopt a design such as the Type 22 variant. The merchant ship conversion would cost about £5,000,000 per installation while the SWATH and the frigate variant would cost about the same as a conventional warship of about the same size, currently about £100,000,000, which would purchase a self contained air-capable ship with great versatility.

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THE EMPLOYMENT OF JET VSTOL AIRCRAFT AT SEA

PART 7

THE NEXT AIRCRAFT

SUMMARY

The reprieve of the fixed-wing Fighter/Ground Attack aircraft at sea gives grounds for predicting that it will eventually need a successor in the same mould.

Achieving growth in performance by means of increases in size alone will be limited by the dimensions of the ships from which it may operate, but fortunately both the engine and airframe of the current aircraft have the potential for improving their performance without necessarily getting very much bigger. The next aircraft will continue to be launched by means of the skijump, and so it will be propelled by a vectored-thrust system. It is argued that a single-engine installation remains the best system.

For the aircraft to be a success its Reliability and Maintainability must be specified with as much care as is afforded to other parameters like Weight, Size and Performance.

The design requirements resolve themselves into two types of aircraft in direct contrast with one another; one having a high load carrying capability and manoeuvrability, the other having good straight-line supersonic performance. This will be facilitated by use of Plenum Chamber Burning in the engine. Both types of aircraft could be developed from the current example, the former being available for order already while the design potential is ready for the latter.

'Cheshire puss,' she began, rather timidly, as she did not at all know whether it would like the name; however, it only grinned a little wider. 'Come, its pleased so far,' thought Alice, and she went on. 'Would you tell me, please, which way I ought to walk from here?'

'That depends a good deal on where you want to get to,' said the Cat.

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INTRODUCTION

To leap straight in to a study of what sort of aircraft should succeed the Sea Harrier without first allowing some sort of preliminary discourse is to beg the question of whether in fact anything might succeed it at all. Only when this has been answered positively may we proceed to further considerations such as should the successor be an extension of the Sea Harrier itself, or should a totally new line of exploration be opened.

To ask whether the Sea Harrier should have a successor designed to take over from it means reopening the question of do we need the Sea Harrier in the first place. There can be no doubt that it would never have come to be built had not the Harrier already been in existence as a base from which to develop it; certainly no STOVL aircraft could have been conjured up from scratch in time to meet the Naval Staff Requirements, and this implies that the existence of this aircraft as a Naval Weapon System is not based on a foundation as firm as that of others which have been in service before it. It is not the latest in a line of Naval aircraft filling a specific and established role, instead it is the first member of what only may be a new generation, it might not found a new dynasty at all. In this it has the same sort of singularity as those earlier innovations the Flying-boat fighter and the Mixed Powerplant Interceptor. In sharing their special characteristics of uniqueness there is a risk that it may also share their vulnerability.

It will be recalled that as a matter of Defence Policy the development of fixed-wing aviation in the Royal Navy was officially brought to a halt some fifteen years ago, and so it is as well to bear in mind that the arguments supporting such a move as a sound strategy showed themselves to be viable then, and could do so again.

All the same, in embarking on the final stage of this Study it will be assumed that the proponents of the Fixed-Wing Naval Aircraft are well enough rehearsed in their arguments to overcome counter-claims of the sort put forward in the Defence White Papers of the 1960s, that a replacement for the Sea Harrier will be called for, and that it will take the form of a manned aircraft.

The next question then is of what this form should be. Customarily a move towards development of a weapon system is made in response to a call for more performance. Technical advances notwithstanding, this development is almost always accompanied by an increase in size; the contribution of any advance in technology is that the improvement achieved is far greater than would be accounted for by an increase in size on its own. Thus it came about that the muzzle-loading gun was succeeded by a bigger gun, a breech-loader, and the piston strike fighter, the Firebrand at 17500 lb came to be succeeded by a turboprop aircraft the Wyvern at 24500 lb, which in turn gave way to the twin bypass jet Buccaneer at twice the weight. The trend in size has always been an upwards one.

In the case of the aircraft intended to succeed the Sea Harrier in the sub-capital ship, this trend will be hard to follow, there will not be much room for physical growth. Instead the improvements in performance will have to come almost entirely from the engineering on its own. What must be looked at now is whether the engine and airframe of the Sea Harrier still have enough capacity for development to support a further generation of that aircraft, or whether the solution must be sought in some other, different configurations.

THE NEXT AIRCRAFT

At present the Harrier family represents the only type of jet VTOL aircraft that is operational and undergoing continuing development in the Western World. For that reason it might seem sufficient to limit the field of study to vectored-thrust and nothing else when considering its successor. Other forms of jet VTOL have existed on paper for over 20 years, some have been built and flown, but none has come anywhere near offering a serious challenge to the Pegasus/Harrier combination. That combination might not represent the most perfect propulsion system in theory, but it does work, it is in being now, and it has a long start over all the others. Need we look any further?

But the reason for shelving the earlier designs and configurations was not necessarily that they were not as good as the Hawker/Bristol-Siddley aircraft. Many of them ceased to be developed only because the political requirement for them was withdrawn, not because the technology of their time failed to support the demands of their design. And maybe even if it had, there might be something to be gained by bringing them out in the open again a dozen or so years of research, design and development further on.

It will be remembered that the Hawker P1127 was developed with an eye towards becoming a VTO replacement for the Fiat G91 in the NATO fighter role. This requirement had begun to harden into NBMR 3 (AC 191b) in 1961, and while the P1127 was first in the field in this particular race it was rapidly followed by eager entrants from the Anglo-German, German-Italian and Anglo-Italian stables. At that time the Pegasus engine was Bristol-Siddley's alone, and Rolls-Royce as their competitors were trying as hard as they could to meet the challenge by developing a range of pure lift engines of their own.

The P1127 was set up as the base aircraft for comparison, and was arbitrarily designated VAK-191-A. (Vertikal Startended Aufklärungs und Kampfflugzeug - Vertical Takeoff Reconnaisance and Fighter Aircraft). Its contenders were the VAK-191-B, which had started out as the Fokke-Wulf 1262, with two Rolls-Royce lift engines and a Rolls-Royce/MAN Turbo lift-cruise engine, and the German EWR 420 VAK-191-C together with the Italian G95/4 VAK-191-D, both propelled by straight thrust engines and lifted by a battery of Rolls-Royce lift engines.

Higher up the performance scale were the possible successors to the F104; the VJ 101D with five lift engines and the Mirage 3V with eight. It was not technical infeasibility that brought the development of most of them to an end so much as a belated recognition on the part of their NATO sponsors that, while forward dispersion of VTO aircraft to distributed sites could confer great tactical advantages over the policy then current of operating from airfields well behind the battle lines, this could be achieved only at the cost of establishing a formidable forward organisation for supply, maintenance, control, communication and command, and this cost was more than they had bargained for in their initial enthusiasm for a VTO force.

Later designs of aircraft too should be considered; notably those proposed as candidates for the US Navy's VTOL 'B' concept, as they represent the very latest in design thinking. Either way, it is worth sparing some time to review the alternatives to the vectored-thrust aircraft, even if the result is no more than a firmer determination that it is in vectored-thrust that the future lies.

The question of engine layout is not the only problem to be considered. Aircraft configuration itself must be looked at too. The main headings for further debate are as follows:

1. Attitude at takeoff, vertical versus horizontal.
2. Means of propulsion; vectored-thrust versus other lift/cruise combinations as well as form and augmentor systems.
3. How many engines. Single versus multiple.

Additionally the limitations imposed by the ship environment must be investigated, and the question of Reliability and Maintainability must be tackled at an early stage, not just left to drop out as has been the case in the not-so-distant past.

Finally, and here compared with the more usual processes of aircraft specifications the cart is ahead of the horse, we must consider what the aircraft is required to do and whether the configuration we finish up with will enable it to do it.

Attitude at Takeoff

There can be something very stirring in the image of an intercepter fighter taking off in a vertical attitude and climbing straight up into the sky and away on its missions. There is no time wasted in taxying, in positioning for takeoff, in accelerating down the runway, instead just punch the button and away! This image must have been well to the fore in the minds of the designers of the first VATOL aircraft, the Corvair XFY-1 "Pogo-stick" which flew in the mid 1950s. The XFY-1 was one of two tailsitters produced at that time, the other being the Lockheed XFV-1, and both were driven via a massive counter-rotating propeller. The Convair aircraft, lacking a horizontal undercarriage, could operate in the vertical mode only, while its Lockheed counterpart was capable of horizontal takeoffs and landings, and started its flight trials most cautiously in this attitude. Indeed it never progressed far enough to complete a vertical takeoff or landing.

Once airborne, both aircraft performed as well as expected and the necessary vertical takeoff presented no problem for the XFY-1.

However, recovery to a vertical attitude preparatory to a tail-first landing proved to be very difficult indeed. The Corvair test pilot had experienced problems enough in controlling the aircraft in the upright position even when it was constrained by tethers. (He was not assisted in this by the circumstance that the initial flight trials were conducted inside the hangar).

His biggest headache was trying to establish which way the aircraft was going, up or down, and the best he could do was to develop a technique of twisting round in his seat and judging his height and opening or closing tendency by looking over his shoulder, an uncomfortable and wearying attitude to have to adopt.

With judgement in the vertical being difficult to exercise, Corvair pilots played it very safe, and transitions from horizontal flight to the vertical were characterised by height gains of many hundreds of feet. The subsequent cautious descent, being carried out at a very high level of power, accounted for a very high fuel consumption for this stage of the sortie and so imposed a prohibitive range restriction on this type of aircraft. Each aircraft was evaluated far enough to prove its point and was then retired. The Corvair XFY-1 may now be seen standing alongside the airstrip at the US Navy Base in Norfolk, Virginia.

Vertical takeoff by jet lift alone was accomplished in 1956 by the Ryan X13. Two examples of this aircraft were built and flown quite successfully, demonstrating especially well that vertical takeoffs and landings were quite possible even in a strong crosswind. The X13 was propelled by a single Avon engine developing a thrust at takeoff of 9750 lb. With a thrust/weight ratio of 1.3 (Ref.1), this implied a takeoff weight of 7500 lb, and elementary analysis of the aircraft design and proportions leads to the conclusion that at most 2000 lb of this was fuel. With a fuel flow at max.thrust of some 140 lb/min it can be seen that the endurance of the aircraft was not high, and the state of the engine art at the time was not such as to offer any prospect of making it any higher. Like the Corvair and the Lockheed, the Ryan was not developed any further.

Some 20 years were to elapse before VATOL emerged from retirement, this time among tentative submissions of aircraft meeting the VTOL-B specification. By now, aircraft with a Thrust/Weight ratio at takeoff of greater than unity were not uncommon, and so the possibility of doing without the takeoff run and so dispensing with the long flight deck or catapult while at the same time still retaining the function of the sort of aircraft usually calling for both became very attractive. Of the five conceptual designs put forward for further study (Ref.2), two were for VATOL aircraft; one by Northrop and the other by Vought, and each claimed the advantage of a substantial saving in weight over its HATOL counterpart designed for the same missions.

These savings would be brought about through the aircraft not requiring extra lift engines or provision for thrust vectoring at takeoff and landing, and would not be disputed. The balance is redressed though by the extra demands to be made on the control system of the aircraft and the necessity for major and innovative structural changes to be made on the parenting ship. The recovery manoeuvre of the aircraft calls for it to be controllable at angles of attack as high as $+100^{\circ}$, while the structure from which it launches and to which it returns needs an elaborate system of gantries and ground equipment, even, in the case of the Vought aircraft, a platform deck able to be tilted through 90°.

It is in this latter respect that any case for such a VATOL aircraft to be procured for the Royal Navy must fail. The arguments for any sort of ship modification other than a static skijump have been tried out and soundly beaten. Such alterations to a small ship carrying just a single aircraft could not be justified, the reason being that its utilisation would be too low to warrant the expense, while a ship carrying three aircraft or more, the smallest number able to sustain a role as a credible airgroup would be big enough to mount a skijump.

So for the Royal Navy at any rate, and for any other fleet committed to launching by skijump, the VATOL aircraft must be turned down and the vertical takeoff aircraft will continue to be, to introduce another vogue term in this field, a Flat Riser.

METHOD OF PROPULSION

There have been five different types of propulsion system devised for VTO aircraft, and each one has carried with it the belief of its protagonists that in its own particular application it is superior to the other four.

Each system has strong features to recommend it, and even now, with vectored thrust so well established as the most successful with more than 300,000 flying hours to its credit, if they were all compared on their theoretical merits alone it would still be difficult to decide on which one was best. But as we have seen when comparing auxiliary launching systems or types of ship, judgements must take established records into account together with the development that has gone into them. And on that basis, a system which performs well enough now but with some admitted shortcomings must be preferred to another which might look more promising in design and model form but which would take time and effort to prove itself.

The propulsion systems eligible for consideration are:

1. Lift augmentation by Ejector
2. Lift by Fans
3. Lift by jet reaction, of which the subsets are:
    a. Lift engines and cruise engines
    b. Lift engines and lift/cruise engines (which type includes the GE.Remote Augmented Lift System).
    c. Lift/cruise (i.e.vectored-thrust) engines alone.

Many parametric studies have been carried out to compare the relative merits of these systems of propulsion as applied to a common aircraft designed to common ground rules. The relative placings in order are very dependent on the mission of the aircraft, especially the amount of fuel it must carry, and it can be fairly said that no one system towers above the rest. (If one did, there would be no case for pursuing the others). Concerning jet reaction systems, a mixed system, i.e. one using extra lift sources, usually comes off best, but the lead it shows over the others can be well disguised in the final presentation by use of such devices as suppressed zeroes, cleverly restated parameters and the like (Fig.1).

For our present purposes the non jet-reaction systems will be considered first.

Ejector Systems

These worked well enough in the Lockheed Humming-Bird to be carried forward for the lightweight supersonic shipborne fighter project the XFV-12A. Unfortunately the promised amount of lift augmentation on which the aircraft depends has not been achieved in practice. Every year it fails to work puts it a further year behind the established systems of lift plus lift/cruise and vectored-thrust which continue to grow in experience and confidence. By the time lift augmentation has shown itself to work, if ever it does,

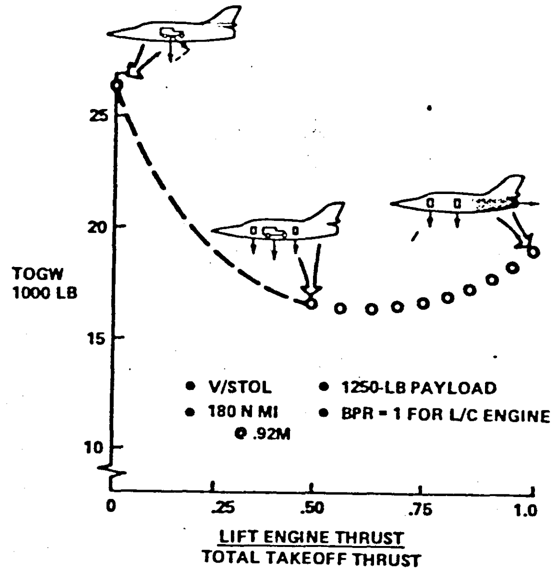


FIGURE 1a

taken from a study favouring Lift + Lift/Cruise (Ref.3)

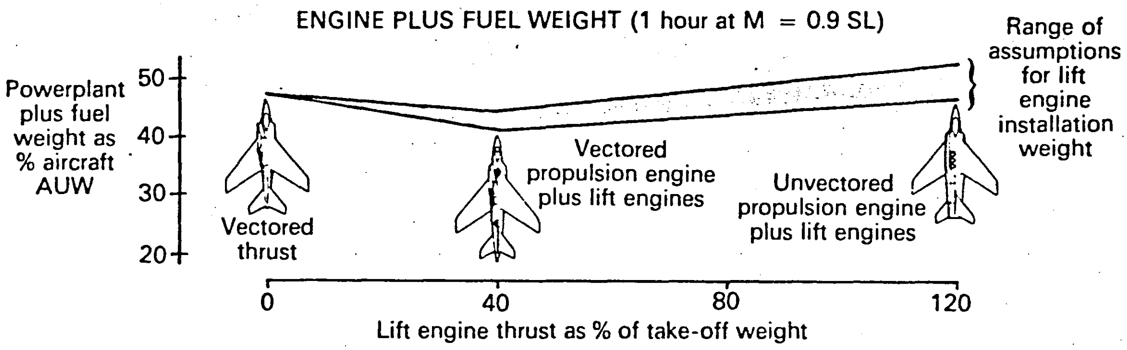


FIGURE 1b

taken from a study by RR and BAC (Ref.4).

FIGURE 1. MERIT OF VECTORED THRUST ENGINE AS A PRIME MOVER

it will lag a dozen years behind vectored thrust, and what it has to offer is not spectacularly better.

Lift Fans

The lift fan idea as demonstrated in the Ryan aircraft of the past decade or so has much to recommend it. Originally introduced in the form of lift fans in the aircraft wing producing the major part of the lift for takeoff and landing, the tip-driven fan offers itself as an attractive alternative to a separate lift engine in, for instance, an aircraft powered by a Lift plus Lift/Cruise system (Ref.3); where the bulk of the propulsion system can be located way aft in the airframe thus clearing the way for area-ruling and transonic flight, and a need arises for a source of balancing lift at the nose. In this application the fan has the edge over the lift engine in not needing a separate fuel system, either engine or airframe, and of being more efficient aerodynamically (higher mass flow moving more slowly), while on the debit side it does need a transfer duct from the main engine by which it would be driven.

Batteries of retractable lift fans have appeared in projected designs for short haul aircraft, notably the HFB (Hamburger Flugzeugbai - makers of the Hansa 320 executive jet) 72A, which shows four sets of two fans which are deployed in the horizontal plane for landing and takeoff, and retract vertically into the fuselage during flight.

In the Ryan XV-5 aircraft itself the fan-in-wing layout presents features which could well suit it for development for use in a faster interceptor fighter. The fans are both broad and shallow, with only a slight taper in the blade. This means that the wings into which they are fitted would themselves be of a broad chord measurement while remaining relatively thin, and for a given area the span would not need to be much greater than the diameter of the fin. In short the wing appropriate to this system would have a small t/c ratio combined with a low aspect ratio, both of which satisfy the requirements of a high speed aircraft with no call for extreme agility. Had there been no other contenders in the field this design could well succeed, but other contenders there are, and if there is a future in high speed aircraft for the lift fan at all, it will be as a source of auxiliary lift for balance, not as a generator of primary lift.

Jet Lift and Propulsion

Three varieties of jet lift have to be considered. They are the lift/cruise system by which one set of jet nozzles serve both to lift the aircraft from the ground and to propel it in wingborne flight, the lift plus lift/cruise system, in which a lift/cruise system is augmented by one or more dedicated lift engines which are in use during hovering and transition flight only, and the lift plus cruise system, with the lift and propulsion function being completely separate.

It is difficult to claim superiority for any one of these systems over the other two. The engines cannot be considered in isolation because as systems they make widely differing demands on the configuration of the airframe for which they are intended, and there is no true way of evaluating the costs of these different configurations other than by full-scale experiment, while a small alteration in specification of the mission for which the aircraft is intended, especially when it ventures into the transonic and supersonic regions, can completely upset the original order of merit.

As stated earlier, general considerations of the problem usually found the lift plus lift/cruise mix of engines to offer the lightest and therefore, in this context, cheapest propulsion system for a projected aircraft. The lift/cruise system was usually found to be uneconomical because the power essential for lift was well in excess of the power required for cruise and therefore it was poor economics to have both functions performed by the same engine, while at the other extreme, having a separate battery of engines for lift alone while making no use at all of the main propulsion engine at takeoff and landing, found firmly against lift plus cruise. This is where the arguments in support of Plenum Chamber Burning begin to find their force, that to use P.C.B. for only certain segments of the flight, notably takeoff and landing, (but also possibly in supersonic flight as well) would be in effect to generate an extra lift engine when required, and so to move the lift/cruise system into the zone of improved economics of lift plus lift/cruise.

While a lift plus lift/cruise system can sometimes be shown to provide the most economical design for an aircraft it also exposes it to all sorts of problems. Having extra control systems for the extra engines is hardship enough, but the most taxing area for pilot and operator alike appears to be in transition. The L + LC aircraft has to handle the transfer of weight from lift engines to wings with great delicacy. At the peak of the hover the aircraft must still be in a horizontal attitude or at least one perpendicular to the axes of its lift engines, otherwise it is not using them to their full advantage. As it begins to move forward the momentum drag of its lift engines exerts a destabilising nose-up moment which has to be countered by a positive nose-down order, which means that the mainplane is presented to the airflow at a depressed angle of attack just at the stage of flight where an elevated angle of attack is called for. The accelerating force by which this transition is expedited comes from an engine which has been optimised for the high speed cruise end of the operating spectrum, so the acceleration is not very great, and the transition takes a long time and a long distance before it is completed. Times of over 1 minute and distances of over 1 mile have been reported for the Forger, which is limited to taking off vertically. During the whole of this manoeuvre such an aircraft is exceptionally vulnerable both to breakdown from within, where everything is running at full power and speed, and from without, where it presents a sitting target.

With the only newcomers on the propulsion scene being the Remote Augmented Lift System and the forward-mounted Lift Fan, both representing alternatives to the auxiliary lift engine, if all other considerations were equal then the field from which to choose the propulsion system for the next RN aircraft would be wide open.

Other considerations are, however, not equal as far as the RN is concerned. In choosing to commit itself to the skijump as its VTO launch platform, the Navy has committed itself also to limiting its aircraft only to those whose propulsion systems are compatible with that skijump. That means an aircraft which can use all its thrust for acceleration along the takeoff deck and then vector all its thrust for support and acceleration during ballistic flight.

That effectively rules out any system using lift engines or equivalent lift producers. These do not contribute to horizontal acceleration along the deck, and once the aircraft has left the skijump they develop a major thrust component dedicated not to accelerating it but to slowing it down.

What remains is the RALs installation (but only if the RALs nozzle can be pointed backwards far enough,) and the balanced vectored-thrust system.

(There is another possibility worth noting. We have become accustomed to thinking of thrust vectoring as being something brought about by swivelling the exhaust nozzles of the engine relative to the aircraft, or even swivelling the engine itself. It can also be accomplished by tilting the whole aircraft. There are now aircraft coming into service with low aspect ratios and partial slender delta wings which together enable them to fly at extremely high angles of attack; the F18 has been demonstrated to be controllable at 68°. This being so, then such aircraft with a high enough Thrust/Weight ratio should be able to launch from a skijump, rotate through a further 40° or so, and following the right flight path profile gain the same benefits as a V/T aircraft of similar characteristics. A conventional recovery would be made at a different site.)

The vectored-thrust system is already predominant in its sphere, and if it has room for improvements, (as it indeed has, as will be shown later), that is where the development must lead.

The Task Force set up by the US Undersecretary of Defence for Research and Engineering to study V/STOL technologies and their impact on new configurations of combat aircraft found as follows: (Ref.6)

> 'The technology will currently support significant improvements in those aircraft configurations that are not radical departures from existing classes of V/STOL aircraft, notably variations of --- the Harrier'.

This can only mean that they agree that vectored-thrust still has a lot of development potential as yet untapped.

How Many Engines?

One of the first nails in the coffin of the Hawker P1154 was the insistence on the part of the Royal Navy that all its new generation fixed-wing aircraft should have two engines. This had to apply to the P1154 and the design of the aircraft had to be upset by removing the scaled-down BS100 originally intended for it and devising instead a fitting for a siamesed pair of Rolls Royce Speys. This split the Naval version away from the Air Force one, and led eventually to the cancellation of both versions of the aircraft while the Navy settled for the F4 Phantom and the RAF ended up with the Buccaneer.

At first sight it appears to be no more than simple common sense that two engines are better than one. ' If you lose one you can still get back to base on the other', is the way the reasoning goes. The Service has developed a reflex of asking for a multi-engine fit if at all possible, and feels that if the aircraft ends up with only one engine after all then the design represents a backward step, and safety has, regrettably, been compromised.

Engines now are a lot more reliable and long lived than they were when the enthusiasm for a multi-engined fit was first fired up, and the case in support of a single engine is worth looking at anew, if only to offer reassurance that an aircraft of the Harrier type is not inherently unsafe.

Historically, as far as military aircraft at any rate were concerned, the reasons for building aircraft with two or more engines were not primarily a concern for flight safety, they were simply that the aircraft needed more power than a single engine could provide, or, in one case, that a twin installation was the only design that would permit the installation of a forward firing gun. (It was a slightly different story for civil aircraft where the trend was to go for three engines if one was not enough, thus making the loss of a single engine survivable).

Even if an aircraft could fly with one engine out it did not follow that it was fully operable. It was not uncommon in a twin-engined aircraft to have one driving the electrics and the other driving the hydraulics. This concept of twin-engined unreliability persisted right up until the 1950s where it was a feature of the Navy's Short Sturgeon. Multi-engined integrity did not begin to take on its current meaning until the emergence in the 1940s of aircraft like the Constellation airliner in which every engine drove an individual set of services, and the hydraulic,pneumatic and electrical systems could be sustained satisfactorily with one engine or more out.

In the early days of VTO aircraft, operation of a multi-engined system was not just a precaution, it was a necessity borne of design. Lift engines when fitted were purposely meant to be small, light and prolific, and the philosophy was that loss of any one could be covered by slight overspeeding of those that remained, it being appreciated that in the hover there is no such thing as an acceptable reduction in performance analagous to that which may be tolerated when an engine fails in conventional flight. The more lift engines there are the less extra effort is needed of each one. Hence we find four lift engines in the SC-1, while the Balzac had eight. Later, development of more powerful lift engines caused that design policy to be adjusted. The biggest threat seen from loss of a single engine had been that of uncontrollable roll, and the design case was covered in which failure of one engine could be met by throttling back its opposite number. Now, with fewer engines producing the lift, they could be disposed along the centreline of the aircraft so that roll would not be a problem if an engine failed while the accompanying movement in pitch would be more controllable as a larger Moment of Inertia was involved.

There is no disagreement that flight safety will benefit if an aircraft can survive the loss of one engine even at the most critical phase of its flight. But if the probability of this occurrence is very low, what penalty has the operator burdened himself with in his efforts to back up the serviceable belt with an equally serviceable, and expensive, pair of braces? The answer can be provided by examining the statistics.

If the probability of a defect in a single engine is P then the probability of a defect in a second engine during the same period is P^2. If this was a catastrophic defect then the survival probability of the aircraft has increased from (1-P) if it is a single engined aircraft, to

$(1-P^2)$ if it is a twin. As P is less than 1 then the twin is clearly safer, by a margin of $(P-P^2)$, i.e. $P(1-P)$; or if P is very small, as is the case for a catastrophic defect, the margin ≃ P. What is the cost of this tiny increment? The distribution of defects in this example is as follows:

	Single engine	Twin
0 defects	$(1-P)$	$(1-P)^2$
1 defect	P	2P
2 defects	0	P^2

So although the safety of a twin in better, by a tiny amount ≃ P, being the probability of an engine failure, the defect rate is increased also by P, but P can now relate to any type of engine defect and is far from tiny.

Simply stated, there is twice the likelihood of something going wrong in a twin, this implies that it will suffer twice the Downtime, and Downtime, as demonstrated in Part 4, destroys Availability.

Thus it comes as no surprise to learn that information from the Maintenance Data Centre shows that, for instance, the Defect Rate in the Propulsion and Engine Start systems for the Jaguar (2 x Adour) is well over twice that for the Hawk (Single Adour), that the rate for the Nimrod (4 x Spey) is twice that of the Buccaneer (2 x Spey) and that the manhours expended per flying hour on unscheduled work are in the same proportions. The maintenance penalty of these systems averages something over 20 manhours per defect, so the effect upon Downtime, and hence upon Operational Availability, is bound to be very severe.

In a conventional aircraft it is agreed that failure of a single engine need not be disastrous if a second engine can bring it back safely. The same would apply to a twin engined VTO aircraft. Even if loss of an engine made it impossible for it to hover it could still safely be brought back to a rolling landing. But if the system of operation is one in which all recoveries are vertical, this defence too of the twin-engine installation crumbles.

However, settling for a single engine rather than for two should not be regarded as settling for second best. Even apart from causing the operator less trouble the single engine powerful enough to do the work of two smaller ones has many advantages of scale.

Curiously, a saving in weight is not one of them. Study of the characteristics of engines in current service shows that they are all described quite well by a relationship such that Weight = (Takeoff Thrust) ÷ 5 or 6, and that one big engine weighs the same as a lot of little ones for the same total thrust, e.g. the Olympus 593 producing 37000 lb and weighing 7500 lb is about as heavy as ten TFE-731s each producing 3700 lb and weighing 755 lb.

While consideration of weight then does not appear to influence the choice of how many engines to fit, this is not so for size. Further study of engines in the current military inventory shows a relationship between engine diameter D in inches and Max.takeoff thrust T in thousands of pounds of

$$D = 20 + 1.06T$$

so that a designer meeting a requirement to house 3000 lb of thrust can choose between one engine with an installation width of 50 inches or two with an installation width of at least 70 inches. If his aim is to produce a slender fuselage with a clean tail end then a single engine will surely be his choice.

The large engine has many advantages in its own right over a smaller one. Its compressor blades will be bigger and better able to withstand impact damage, its tip clearances can be more closely controlled, its blading can be cast to a more accurate profile, and shaping its turbine blades for air cooling can be done to finer limits. Its bearings will be bigger and more rugged, and the whole power plant will be easier to adjust as well as inspect.

Finally on this topic it may be stated as a clinching argument that if there were a sound case against the single engine there would not be so many aircraft in use, civil and military, propelled that way.

RELIABILITY AND MAINTAINABILITY

The Reliability and Maintainability of the last generation of fixed-wing fighting aircraft of the Royal Navy, the Buccaneers and the Phantoms, were very poor indeed. The natural state of an aircraft was to be unserviceable, and the Squadrons were fully geared up to accept defect reports from every aircrew member, Pilot or Observer, as he walked in off the Flight Deck after a sortie. What is curious in hindsight is not that this was the state of affairs of the time, that our million-pound aircraft was expected to go wrong every time we used it, but that this was accepted as normal, and almost became regarded as a cause for self-congratulation,'Our aircraft are so advanced that we need to have men working all around the clock to keep them serviceable'.

Such unreliability could scarcely be contained by all the vast resources of a Fleet Aircraft Carrier, so there can be no question that it could ever be kept in check by the facilities of a much smaller vessel. While there are encouraging signs on both sides of the Atlantic (but mostly on the far one,) that Reliability and Maintainability are at last being brought to heel, the practical results of coming to grips with these problems are still a long way in the future. There are still no aircraft in Naval service in which quantitative values of these parameters were used to play any part at all in any phase of design or development.

It could be claimed, and rightly so, that target values for these qualities have been set in recent years for aircraft of the current generation, and hopeful attempts have even been made to have them subject to contractual agreement with the Aircraft and Equipment manufacturers, but in all these cases the values used have been solely projections of what previous aircraft of a similar type have returned, sometimes marked-up by a factor to allow for improvements in 'State-of-the-art'; they have not yet contributed to the mainstream of design. All that must change.

It was shown in Part 4 of this study, 'Availability', how the operational ability, indeed the very feasibility of an aircraft depends so crucially on the Mean Time Between Defect never falling below certain critical values and the Mean Times to Repair never rising above them. In the cases illustrated actual current values of MTBD and MTTR were used to show what the corresponding Availability, measured in terms of task achievement, would be expected to be. In a proper systematic approach to aircraft procurement it should, of course, be processed the other way round. The Availability should be stipulated, and from this would come the minimum values for Reliability and Maintainability that would permit its accomplishment. These values would form part of the Staff Requirement, along with parameters of size and performance, and having been established by scientific means they would rate equal importance with those parameters.

Before this approach can be implemented there is a lot of ground to be cleared, and a lot of woolly definitions to be combed out.

First of all the definitions of the basic terms need to be agreed on by all parties. Nearly 25 years since the first AGREE conference there is still no common consensus on just what sort of aircraft malfunction should be classed as a 'Defect' and what sort as a 'Failure'. Nor is there a standard convention on whether measures for assessing Defect or Failure rates should be based on Flying Time, Running Time, or simply ownership Time. Only when definitions for these parameters have been set in firm foundations can

can customer and contractor work together in full harmony to develop the aircraft they want.

The latest (1980) attempt at standardisation comes in U.S.Defence Department Directive 5000.40. In this it is recognised at last that a 'Defect' and a 'Failure are not loosely interchangeable, and that if an aircraft is designed by multiplexing say, to tolerate defects then this should show up in its measures of Reliability. So 'Reliability' is defined to cover all malfunctions in all cases, while 'Mission Reliability' (which will be much higher), covers system performance for a specified mission, and allows malfunctions to occur without penalty so long as they are successfully compensated for by alternate (i.e. standby) equipment and modes of operation. That such a simple distinction has taken so long to arrive on the scene will indicate to the newcomer to this topic the extent of the confusion that reigns at present.

Unfortunately, even this attempt in precision does not go far enough. It is sound enough to recognise that there should be two distinct categories of malfunction to be counted namely

(a) Things that went wrong with the aircraft regardless of whether they interfered with the mission or not, and

(b) Things that went wrong with the aircraft and did interfere with the mission.

It misses out a third and most troublesome subject, namely:

(c) Things that went wrong with the aircraft, did not interfere with the mission, but nevertheless must be fixed before the aircraft is fit to despatch on another mission.

These, which may or may not include category (b) arisings, are the ones making the largest contribution to the inter-mission Downtime and accordingly are the ones to which the Availability will be the most sensitive. It is to be hoped that if a UK equivalent of Directive 5000.40 is in course of preparation then this omission will be made good.

While legislation for Reliability improvement is being sorted out, design for Reliability can be set in motion independently. We can thank advances in State-of-the-Art for many reliability improvements demonstrated by current generation aircraft over their forebears, improvements which would have come about regardless of the development of Reliability as a separate branch of science. But the problems can be solved within the state of the art by analysing current defect and downtime data and seeking solutions there also. Thus it is that the F-18 for example owes as much of its high and on-target MTBF of 3.7 hours to state-of-the-art advances as it does to the analyses that led to raising the design scatter factors on structures assessed as critical and using selected derated components, having over 7000 fewer parts in each engine than in the F4, reducing the number of types of fastener from 210 to 50 and making the panel fastenings completely sailorproof by using ¼" section fasteners in lieu of the previous size of 3/16".

The reliability of the Harrier is at present five times worse than the F-18, but it has been shown that selective use of data enables demonstrations of realistically high availabilities over short periods of operation. The successor to the Harrier will be able to do far better, but only so long as the problems are properly identified and taken in hand early enough.

THE HARRIER SUCCESSOR

Before attempting to specify the characteristics required of the successor to the Sea Harrier it is necessary to recollect what that aircraft itself was expected to succeed. While the 'Ark Royal' was still in commission she operated two types of fighting fixed-wing aircraft, and they were very different from one another. Her fighter was the Phantom F4K, supersonic, high altitude, high rate of climb, with afterburning engines and carrying air-to-air missiles, while her strike aircraft was the Buccaneer MK.2, transonic, very low altitude, very heavy, no pretensions to combat persistence or nimbleness, high by-pass engines and carrying a vast and varied weight of air-to-surface weaponry including the nuclear store. It has to be admitted that by no stretch of the imagination can the Sea Harrier be regarded as a successor to either of these Titans, let alone both, regardless of its Fighter/Reconnaisance/Strike designation; indeed it would have been demanding a lot of the aerospace industry to produce a single successor to this pair of aircraft at all, let alone one capable of performing a vertical takeoff and restricted to making a vertical landing.

It is probably a safe bet that in contemplating a second generation of seagoing STOVL aircraft the Royal Navy would wish to resume its aerial activities where they left off when the Squadrons of Ark Royal flew ashore for the last time, and that the aspirations of any other Navy bent on venturing into VTO would follow along similar lines. The design requirements called for can be met by a single type of aircraft only at the cost of a lot of compromise. They could be met much more readily by two.

Even so, the task of defining these two roles is not an easy one. Defining the aircraft to suit each individual role is more straightforward, but success in defining the aircraft is only as good as getting the role spelt out correctly in the first place.

Of the roles to be considered, the one of Strike/ Reconnaisance is the easier one to specify. A surface target whether stationary or mobile need be located in only two dimensions of space. Even the slowest aircraft can outrun it. That aircraft then does not need speed so much as range, climbing performance so much as carrying capacity, agility so much as persistence. An aircraft design satisfying this description will have a big wing, thick and moderately swept, with relatively high aspect ratio and comparatively low Thrust/Weight ratio.

Setting the ground rules for the Fighter is far more difficult because the requirements of this role can call for two models, on the one hand the Air Superiority Fighter and on the other the Interceptor.

The role of the Air Superiority fighter is to engage and outmanoeuvre its opposite number from the enemy camp. It needs agility, persistence and turning performance and it will get these attributes from a relatively thick wing of high aspect ratio, (to minimise span loading and hence induced drag in sustained subsonic high-g manoeuvres). In these characteristics it would not be irreconcilable with the strike variant. Air superiority is not, however, the prime role of the fighter at sea. There the target to be engaged is a supersonic bomber which must be intercepted at an extreme range before it gets close enough to launch its anti-ship weapons, and in designing the fighter to oppose it, manoeuvrability, persistence, endurance, all must be sacrificed in order to produce a highly-swept, thin-winged manned missile able to take out its target at the first pass.

The qualities which fit it for this role also suit it for a low level function. High Thrust/Weight, high sweep and high wing loading are what is required if an aircraft tasked to execute a high-speed strike against a designated objective at long range.

So here we have in effect four roles which can be filled by a mix of two aircraft. The big-wing, manoeuvrable persistent sub-sonic model can act as a reconnaisance hunter-killer, (maybe the old designation of Scout should be revived), as well as an air-superiority machine,while its faster high-wing-loaded variant can act primarily as an interceptor and double in the role of high speed strike.

For suitability for flight off a skijump these two conceptual aircraft would be just about evenly matched, the low thrust of the first being compensated by its low stalling speed, the high thrust of the other accelerating more swiftly towards its higher stall speed.

To distil the essence of these aircraft into a single all-purpose design is to aim for what must be a compromise. But the realities of defence economics are such that a compromise it must be, and it will be the task of the Naval Staff to set out their requirements of the next aircraft in such a way as to assist the designers to devise the happiest compromise possible. Can this design follow on from the Sea Harrier itself?

The Pegasus Engine : Room for Development

There is still enough potential stretch in the Pegasus engine to carry it through at least one generation more, and possibly two. Its record of growth is remarkable already. As the Pegasus 1 on its test stand it developed 9000 lb thrust, and progressive evolution has brought this up to 21500lb from the Pegasus 103. Two further steps already planned would increase its output still further to 25000lb in the form of the 11-35 engine as schemed for the AV-8B, and that is still without recourse to any form of reheat.

Supersonic flight will call for more thrust still. The Pegasus can generate this by employment of Plenum Chamber Burning. This was a feature of the full-scale BS 100 engine in the days of the Hawker P1154, and a total thrust of 40,000lb was expected from it.

Addition of PCB brings with it its own set of problems and challenges. An attribute of the dry Pegasus installation is that the relatively cool air blown downwards from the front nozzles acts as a screen between the extremely hot exhausts of the rear nozzles and the engine intake. This is particularly useful when in the hover, as it serves to limit the temperature rise at the intake due to recirculating air which, if unchecked, would cut back heavily into the thrust delivered. If the air from the front exhausts is to be at high temperature as well, as is the case with PCB, and this is allowed to circulate without restraint, then the total loss of thrust due to hot gas ingestion would more than offset the rise in VTO weight that PCB was expected to confer.

Much of the research conducted by the engine manufacturers, initially at their own expense after the P1154 had been cancelled and then latterly after interest in VTO aircraft has been rekindled enough to stimulate an injection of Government funds, has been directed towards seeking a solution to this problem of reingestion. One remedy that has been considered is to angle the front jets inwards, towards each other. This would have the effect of destroying the fountain that gives rise to the recirculation; unfortunately at the same time it reduces the underbody lift that is a useful byproduct of fountain impingement. But on balance the total loss is estimated as being only 8% of the expected thrust, and the Pegasus

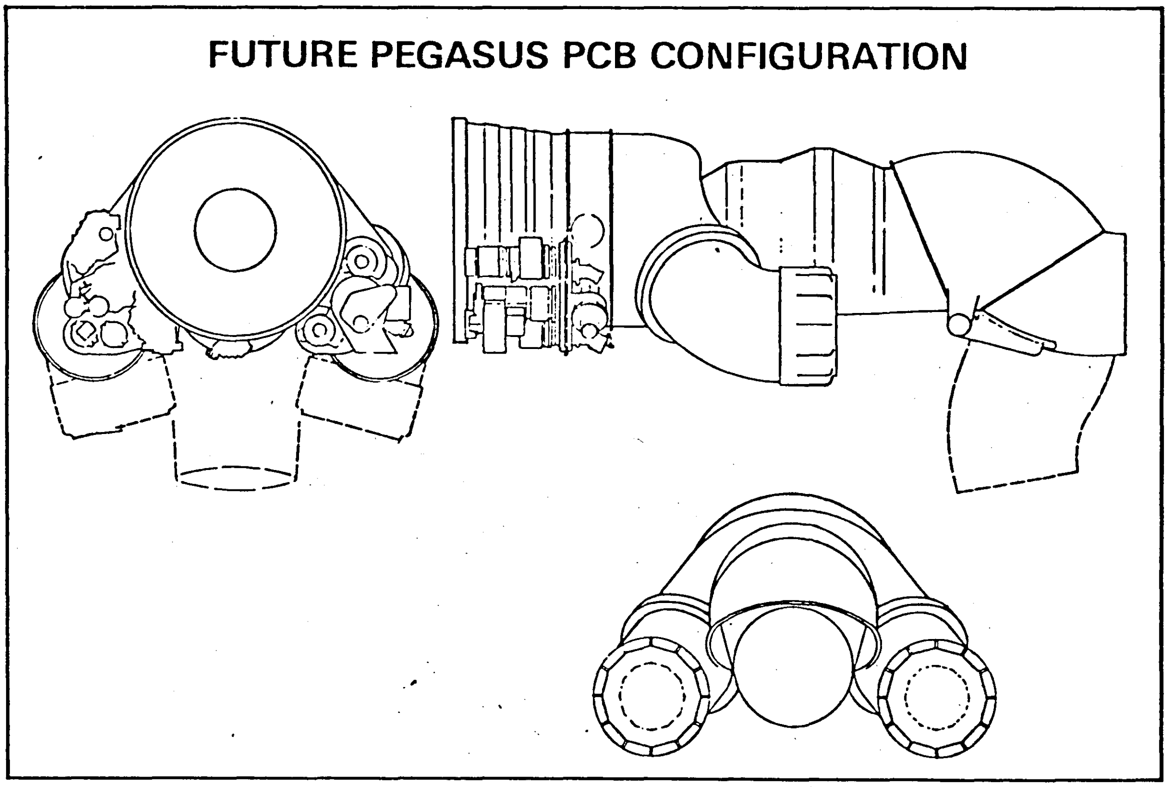
11-35 with PCB is still expected to deliver thrust to the tune of 34000lb.

The cost of installing PCB presents a formidable challenge. The thrust per pound of air of the bypass engine is already low as a consequence of designing for a condition of high mass flow at low speed. PCB makes things worse on this count, the engine demands an airflow 3x that of the equivalent optimal turbo-jet cruise engine, and therefore needs an intake area and cross-sectional area to match. The sfc with reheat is about double that of the dry engine, meaning that the increase in fuel flow rate itself is even higher still, although this increase is not as great as would result from a high-temperature afterburner.

But this cost must be paid if the added performance is essential, and the increase can be kept to a minimum if the correct design strategy is followed. An engine with PCB available to it can be more economical in cruise conditions than a dry engine of equivalent output, because the dry engine would be operating in a throttled condition. It is best therefore to design the system so that as much of the envelope as possible is covered by the unboosted engine, conserving PCB for the far limits, the high speed dash, takeoff, and, if necessary, landing. Such an approach would make the engine attractively economical to operate in 'peacetime' conditions, as high-speed flight at the extreme of the operational envelope could effectively be rationed.

An incidental benefit of PCB arises from the fact that in hovering and transitional flight the thrust centre of the engine is further forward than for the dry engine. The requirement for auxiliary pitch control by reaction nozzles can now be satisfied by a single one sited at the rear. Here it exerts its effect over a longer moment arm than at the front, so its force requirement will be smaller, and such an arrangement, in avoiding the weight and installation problems associated with a forward reaction nozzle, avoids too the threat of the intake air becoming contaminated by hot gases discharged from it and deck debris disturbed by it.

A possible and proposed structural development of the Pegasus would be to combine the after pair of jets into a single vectorable nozzle, converting the power plant from a 4-poster into a 3-poster engine. The result would look like the unit pictured in Fig.2, and it could present a less draggy installation than the current two-nozzle system, although the aftermost structure of the aircraft would have to be elevated in design in order to leave a clear exhaust path.



FUTURE PEGASUS PCB CONFIGURATION

FIG.2.

Reference 7 suggests an output of 31900lb for this engine with PCB selected.

The ultimate improvement would be to reheat the hot nozzles as well. This was suggested for the supersonic version of the stillborn AV-16A, and would have increased the maximum speed from M1.5 with PCB to M2.0 with reheat as well. A vectorable afterburner was displayed by MAN Turbo at the Hanover Air Show as long ago as 1968. Tested on an RB 153 it offered an increase of 70% over the dry thrust of the engine. Such an enhancement could bring the thrust of a Pegasus up into the 45000lb bracket. For aircraft limited to the size considered in this study there is no need to venture any further.

The Harrier Airframe : Room for Development

Like its engine, the Harrier airframe has developed over the last 20 years by a process of evolution rather than revolution. The original P1127 stretched itself to become the Kestrel, weight and thrust and counterweight were added to recast it as the Harrier, and another round of structural alteration and improvement produced the Sea Harrier; but what results is still, unarguable, an aeroplane of the 1960s.

The introduction of computer techniques, first as an aid to stability and then as an aid to aerodynamic and structural design has presented the designer with a new range of tools, and the effects of these are to be seen embodied in the shapes of military aircraft launched in the 1970s. The configurations and performances of aircraft like the F-16 and the F-18, the Mirage 2000 and 4000, all demonstrate what can be done with the application of relaxed stability, forward flying control surfaces and computer-assisted wing design, while the Himat research vehicle shows that use of composite materials in primary structure could permit forward wing sweep without fear of structural divergence. The benefits of all these innovations are ready to be granted to the next Harrier, offering improvements in performance of 12% or more, realisable as extra payload, range or speed.

The Subsonic Derivative

One possible next generation is already to hand in the form of the AV-8B and the Harrier MK.5, the so-called "Big-Wing" Harrier. Both of these are well-documented elsewhere and do not need a detailed description here other than to repeat that they are both designed for high subsonic performance combined with a high load-carrying capacity, both are compatible with skijump, and neither is intended to use Plenum Chamber Burning. The future prospects of both designs should become known in early 1981.

The Supersonic Derivative

This still leaves a requirement for a high performance supersonic derivate aircraft to complete the armoury, or at least it does as far as the Maritime operator is concerned. It is neither desirable nor necessary to be too ambitious when attempting to cross the supersonic gap. The aircraft performing an off-the-deck intercept, or intercept vectored from a Combat Air Patrol Station need not be faster than M1.8 (Ref.8). Speeds greater than this use an enormous amount of fuel to reach, and call for the added structural complexity of a variable-geometry intake. Also, aircraft designed for higher Mach numbers suffer higher drag through the transonic region, and their earlier acceleration is slower than that of aircraft which are just supersonic.

The main problem with a supersonic aircraft is the intrusion of wave drag as the aircraft approaches compressibility speed. At supersonic speed wave drag is predominant, accounting for some 60% of the total (i.e. drag is 150% higher than it would be if the compressibility phenomenon were not encountered). Therefore any design consideration that can help keep it down must take precedence over those relating to other aspects of performance, to the detriment of the latter. Thus the supersonic aircraft must have a thin wing (a thickness/chord ratio of 3% offers 37% less drag than one of 5%), losing fuel-carrying capacity in the process, and a slender fuselage (fineness ratio >8), losing fuel space here too, which is all very trying for an aeroplane whose fuel consumption is going to be on the high side. The consequence is that there is no solution to the design problem that produces a supersonic aircraft that is smaller than its subsonic stablemate.

The supersonic version of the Harrier was first planned as the P1150, and then later as the P1154. The next advance was the plan for a joint Anglo-American project to succeed the AV-8A, called the AV-16A. This aircraft foundered due to lack of financial support, but not before a supersonic version had been devised, the AV-16S-6. This is shown in Fig.3 taken from Ref.4. Two problems in producing a supersonic aircraft from a single-engined VTO aircraft are the large frontal area presented by the intakes, even supplemented as they are by the double row of blow-in doors around the circumference, and that the need to have the thrust centre and centre of gravity not too far apart puts the engine in a position such that Area Ruling is difficult to exercise with any efficiency. The area-ruling at the cockpit area is clear from the figure as is the fixed-body intake with boundary layer splitter, indicating a speed of up to about M1.5 but no more. What is less clear is whether the engine is a four-poster or a three-poster. The figure hints at the former, but the slenderness of the fuselage structure aft of the engine could possibly accommodate the latter.

The principal dimensions of this aircraft would have been:

Span = 30 ft
Length = 46½ ft
VTO weight = 28000 lb.

These should be compared with the V-STOL B submissions discussed in Ref.2. These weigh in as follows:

Manufacturer	Span	Length	VTO weight
General Dynamics	37ft	53ft	35000 lb
Grunman	38ft	56ft	37700 lb
Northrop	32½ft	52½ft	30000 lb

These show that even based on the anticipated technology of the 1990s, an aircraft capable of a sustained M1.6+ would still be pretty vast, even though its load is only the relatively low outfit of Air Intercept Missiles and a gun. The conclusion is that a supersonic aircraft is possible to design to a reasonable size so long as the speed requirement is not too extreme.

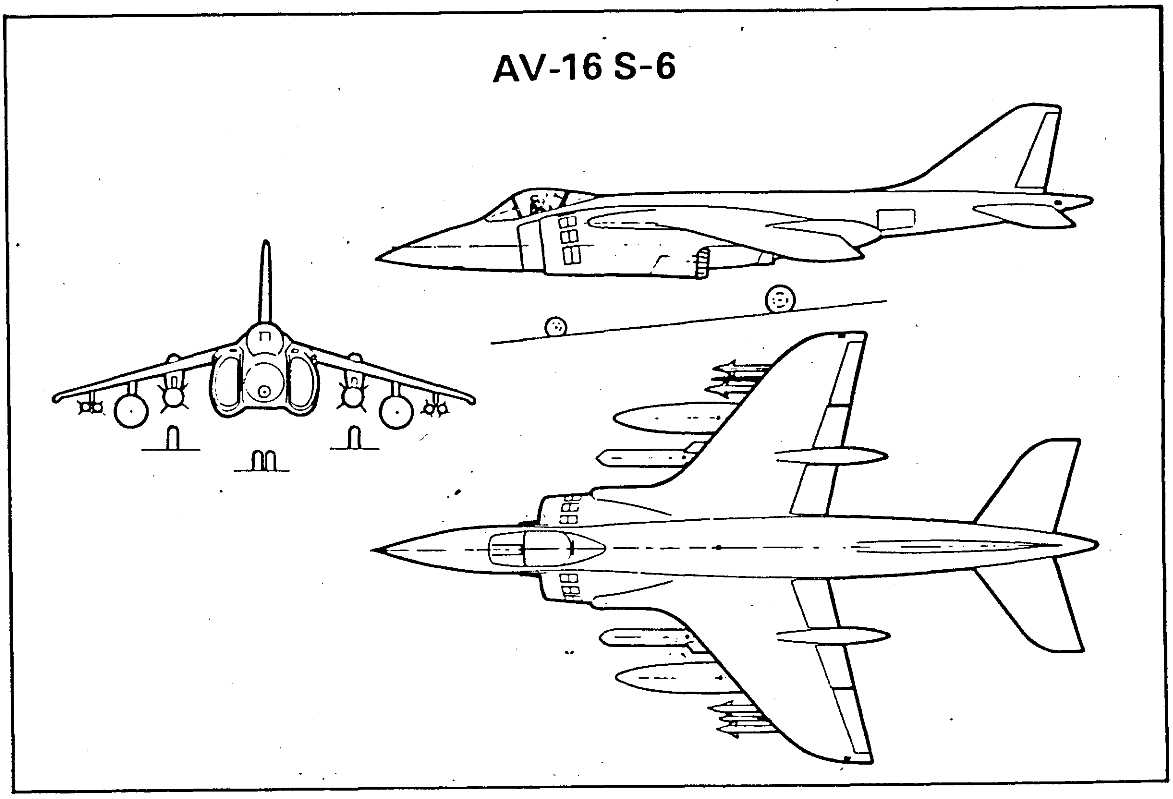


FIG.3

Undercarriage Requirements

The initial success of the skijump owes a lot to the compatibility of the undercarriage of the existing Harrier with the curvature required of the deck. If these features had been completely irreconcilable then it is probable that the invention would never have got beyond the theoretical stage to reach the practical demonstrations that have ensured its success. Where the performance of the current aircraft off the skijump may be restricted by undercarriage limitations, the problem is an engineering one, and as such it will be one amenable to an engineering solution. Full skijump compatibility will be a design requirement of the next aircraft from the very start, as will a suitable hold-back system be if present trials result in the conclusion that one is necessary.

Whether the success of the skijump has had any effect on the design requirement of VTO aircraft for the US Navy is still unknown. At the time of writing nothing has been heard to suggest that the VSTOL B aircraft should be configured to take advantage of it.

THE NEXT STEP

The airframe of the Harrier, like the engine, still offers plenty of scope for performance growth. Unlike in the engine however, this growth is more likely to be rooted in step advances in technology than in established lines of evolution. The application of computer assistance to design can lead to greatly improved wing sections as shown in the Harrier MK.5, and the AV-8B, while the use of new materials can lead to savings in weight like the 20% reduction in the AV-8B wing compared with an equivalent structure of Titanium and Aluminium.

Use of the same sort of advanced composites could permit the incorporation of a swept forward wing with all its attendant advantages of improved airflow free from the threat of physical divergence. (An added benefit of such a wing as applied to the current aircraft is that the new positioning of its main spar would permit vertical engine removal without the wing having to come off first, as CIT studies, yet to be published, now show). Design for relaxed stability means that a smaller tailplane, or better still a canard foreplane could be used. This in turn could lead to a manageable flight path off a skijump being flown with increased efficiency.

All this goes to show that the supersonic version of the aircraft, already schemed in the 1960s and 1970s, could be designed even more effectively in the 1980s.

With the subsonic derivatives of the Harrier already available for the ordering, it is in the supersonic version that the most attractive challenge now lies. There is an undisputed role for such an aircraft in any Service tasked to respond to the threat posed by a long range bomber delivering a stand-off missile, (which description fits any NATO Navy, and most Air Forces as well), and while the price of conventional aircraft carriers becomes more and more prohibitive and conventional airfields are menaced more and more strongly by dedicated anti-airfield weapons it becomes more and more regrettable that the prosecution of such a design continues to be postponed.

"VTOL aircraft will come into operation in a few years time, but in the meantime there will be advances in the performance of other aircraft. It would be the greatest folly therefore to embark on VTOL designs which are limited to subsonic performance".

These words do not look wholly inappropriate to the procurement situation today. That they date from 1960 (Ref.9) only seems to illustrate how little practical progress has been allowed to be made since then.

Official reluctance to recognise the advantages of VTO aircraft over their CTO cousins is a source of surprise. Presumably it is based on an attitude of making judgements from the standpoint of the CTO aircraft representing the established type of flying machine, with the VTO as the newcomer. The main basis of the comparisons is the performance pluses and minuses of the VTO aircraft vis-a-vis the CTO, while its VTOL properties are regarded as only a secondary attraction.

This gives a most unfair comparison. The vital differences stand out in a much clearer perspective if viewed, as it were, from the other end of the pitch. Imagine that it is the VTO aircraft that represents the established order of things,and the CTO is submitted as a competitor. 'Here', the Industry says, 'is an aircraft which will equal, and maybe better the performance of your current one. The only penalty associated with its operation is that your ships will now need the trifling addition of catapults and arrester gear, while your launching sites ashore will have to be extended by about one mile of concrete apiece in order to make it work'.

It would be hardly likely to be greeted with enthusiasm. Looked at this way the VTO fighter/ground attack aircraft emerges as the clear winner, and at sea it is beginning to make a name for itself and its uncomplicated manner of operation. The British, Spanish and Russian Navies already have it, the Indian Navy has ordered it, the Australian and Italian Navies are showing a practical interest in it, while some elements at least of the United States Navy would dearly love to have it.

A second generation aircraft has been shown to be possible, and one able to work from the same ships as the first, an aircraft moreover that could be designed in supersonic form. With only one country in the West actively making and marketing aircraft of this type,it would be a very dreary and unimaginative policy that would reject the opportunity of taking the market lead available to it.

CONCLUSIONS

A VTOL aircraft of the second generation and able to operate from sub-capital ships would continue to make use of the skijump. Therefore its propulsion system would be one of Vectored Thrust.

Limitations of space mean limitations of size. Propulsion by single engine will be both adequate and suitable.

The ideal seaborne aircraft force should be a mix of subsonic and supersonic variants. The technology required for the design of either or both of them is available now.

When specifying such an aircraft the Reliability and Maintainability figures necessary for its operational performance to be a success must be given a prominence equal to that of its more obvious physical characteristics.

Also it must be designed in such a way as to extract the maximum benefit possible from the skijump and not to suffer any limitations due to curvature or normal acceleration loading.

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'If there's no meaning in it', said the King,
'that saves a world of trouble, you know,
as we needn't try to find any'.