AIRCRAFT DESIGN INTEGRATION AND AFFORDABILITY

1. INTRODUCTION

The design of combat aircraft has traditionally been at the forefront of the introduction of new technologies in the aerospace sector. This was true during both World Wars, and perhaps even more so during the Cold War, when the technology race accelerated. In that period, the pursuit of superior military capability, through the use of advanced technologies, had few constraints other than technical feasibility.

The 'victory' of the West In the Cold War, or the collapse of the former Soviet Union, brought the eagerness to earn a 'peace dividend', made possible by the perception of a lesser threat. In fact, the former monolithic, readily identified enemy, has been replaced by a variety of threats, such as proliferation of weapons of mass destruction, regional conflicts and tensions, civil wars and terrorism. Thus upgrades of existing aircraft, and their future replacements, face a wider variety of no less stringent missions.

The increase of the unit cost of combat aircraft has been identified for a few decades as a potential problem. The perception of a lesser threat, and reduced defence budgets, conspire with the wider variety of threats and the cost of advanced to technology, to pose an unprecedented challenge to the combat aircraft designer: to break the increasing cost spiral, thereby ensuring that new generations of combat aircraft remain affordable in sufficient quantities, while still meeting more stringent and diversified requirements.

A brief review of the evolution over the last half-a-century, since the end of World War II, will highlight the cost and technology trends, which have led to the present situation of a difficult compromise between capability and affordability.

1.1. Post-War Evolution

The major strides in aeronautical technology in the last three decades have been accompanied by a significant increase in cost, to the extent that the latter has steadily gained in importance relative to performance. It is, however, important to note that the evolution is dissimilar with regard to the three main components of cost, namely: operations, production and development.

1.1.1. Operations and Maintenance

There is one area of reduction of cost in the last two or three decades: the number of maintenance man-hours per flight hour (MMHFH), which was rapidly increasing since the end of World War Two (WWII), peaked at 20 to 40 in the Vth-generation (e.g. 20 for the F-4 and 35 for F-14, see Table I, p. 7), then reduced to between 10 and 20 in the VIth-generation (e.g. 18 for the F-18C/D, 12-15 for the F-18E/F), and is expected to fall to 10 or less in VIIth-generation (e.g. F-22). Thus, when corrected for inflation, the manpower costs associated with the maintenance of modern fighters have been decreasing appreciably. This is part of a wider achievement; in spite of the increasing complexity and capability of new generations of fighters, there has been in the last two generations a marked improvement in reliability, as measured by the mean time between failures (MTBF). This is not just a matter of built-in (self) test (BITE) and modular design, reducing mean time to repair (MTTR), but is mostly a consequence of greatly improved component reliabilities, outstripping the growth in complexity.

1.1.2. Production and Purchase

The preceding rosy pictured is marred by the fact that upgrade costs of modern aircraft are increasing significantly, in parallel with production and development costs, but at a fraction of the level of the latter. This is what makes aircraft upgrades an attractive alternative to buying new aircraft, as long as such upgrades retain operational usefulness, and allow an extension of service life. One of the increasing components of cost, which was mentioned before, is production cost. It has increased from about US$ 10,000 for a WWII fighter to about US$ 100 million for the F-22: this increase of unit cost by a factor of 10,000 over fifty years is certainly larger than the accumulated inflation over half-a-century, as can be checked by expressing the unit cost of a fighter as a fraction of the defence budget. The problem of high unit cost is well demonstrated by the B-2 price tag of US$ 2 billion, implying that the world's most powerful air force can afford only 20. One can imagine the reluctance to send such a valuable asset to a remote location, where it might come under attack by low cost weapons or face acts of sabotage. Even the B-58, which was stated at the time to cost more than its weight in gold, could be afforded in larger numbers. The B-2 lies at about the same benchmark of costing its weight in gold, but the precious metal has perhaps increased in value faster than inflation.

1.1.3. Development and Testing

The reason for the very high cost of the B-2, is not just the expensive manufacturing technologies, but also the high development cost, amortised over a small production run. In fact, development costs have been increasing even faster than production costs. A WWII fighter could be developed in 6 months for US$ 50,000, i.e. the cost of production of 5 aircraft; over a large production run (over 10,000 for the most widely used WWII fighters), the amortisation of development cost was negligible (even if several variants were produced). A modern fighter takes at least 6 years, costs about US$ 10 billion to develop, and even a US$ 50 million price tag, means that development cost corresponds to the cost of producing 200 aircraft. Thus the cost of development of a new aircraft family has increased by a factor of 40 relative to the cost of production of one unit. The development cost does affect unit cost, e.g. a development cost of US$ 10 billion over a 400 aircraft production run, implies a cost of US$ 25 million per aircraft, to which must be added the actual production cost. In the case of the B-2, the US$ 20 billion development cost, over a 20 aircraft production run, equals half of the US$ 2 billion unit cost. It can be argued that operating cost is much larger, but it is spread over the longer operational life of the aircraft, and it is not so vulnerable to cancellation or cut-back as a new programme. Even so, it is not uncommon for Air Forces to reduce inventories, to be able to develop and field new aircraft: this is not only a question of quality versus quantity, but increasingly often results from a ceiling on total expenditure.

1.2 Present Scenario

The preceding scenario of high aircraft cost applies, with different aspects, to Western Europe, the United States and the rest of the world.

1.2.1 Western Europe

The increasing cost of aircraft development is likely to break the tradition of nations which have maintained a national fighter programme in every generation. The most notable example is Sweden, which, with a population of under 9 million, has pursued a policy of strict neutrality, to the extent of developing successive post-war generations of fighters, viz. the Saab 21, 29 Tunnan, 32 Lansen, 35 Draken, 37 Viggen and 39 Gripen; the latter is considered by the Swedish Air Force as the last of the line of purely national developments, i.e. its successor will have to be developed on a collaborative basis. Even larger European nations, like France, will not be able to afford a new national fighter development programme, after the Rafale. The latter is being developed in a stretched time-scale, and at a low rate of production, after a delayed entry into service, all dictated by financial constraints; technically, the programme could evolve much faster.

Britain has realised earlier the need for cooperative programmes, as shown in successive generations by the Tornado and EF 2000. A factor may have been the political stability of multinational programmes, which makes unilateral cancellation by one nation an unattractive proposition, at least because of the cost of compensation of other partners, and tends to rule out alternatives other than pursuing the joint programme. On a more positive note, although international cooperation increases total programme costs, it still works out cheaper per partner. A rough empirical guide is that a collaborative programme with N partners costs a factor of $\sqrt{N}$ more than a national programme, so that the cost per partner is $\sqrt{N} / N = 1 / \sqrt{N}$ less. For example, in a bi-national programme (like the Anglo-French Jaguar), the cost is increased by roughly 40% (since $\sqrt{2} = 1.4$), relative to a national programme, so the cost per partner is 70%, a 30% saving. In the case of a tri-national programme (like Anglo-German-Italian Tornado), the total cost increases by 70% (because $\sqrt{3} = 1.7$), but the cost partner is 57%, i.e. a 43% saving. In the case of a four-nation programme (like Anglo-German-Italian-Spanish EF 2000), the total cost is doubled, but the cost per partner is halved. The preceding figures are only indicative, since the actual cost saving depends on the degree of programme integration (e.g. only one production line or a production line per country?) and the degree of commonality of the aircraft (e.g. special equipment or versions for some nations?).

It is clear that two similar programmes, like EF 2000 and Rafale, will not occur in the future, whatever the political or national interests, because there will be no resources to support such duplication even if there are differences in detailed requirements. The next fighter generation in Europe is likely to be possible only by pooling the resources of all major countries, even if studies are at present acknowledged by only one: the British FOA (Future Offensive Aircraft), to replace the Tornado - IDS (Interdictor Strike version), under the HALO (High-Agility Low-Observability) programme. This could become either an European or a transatlantic programme, (like the JSF, or the AV-8/Harrier before), depending on which other air force has a deep strike requirement.

1.2.2. United States

Even the world's wealthiest nation is not escaping the effects of increasing aircraft development and acquisition cost. The United States Air Force (USAF) is funding the development of the F-22, and cannot afford simultaneously the purchase of existing fighters in significant numbers; the struggle with F-22 costs is illustrated by the deletion of the two-seat variant, so that pilots will have to transition directly from the flight simulator to the first 'solo' flight. The US Navy (USN) is pursuing a substantial purchase of F-18/F, and thus cannot afford the development of a stealthy combat aircraft. The JAST/JSF (Joint Advanced Strike Technology/Joint Strike Fighter) is unprecedented in that, at the design stage, it is already intended for all three branches of the armed forces: Air Force, Navy and Marine Corps (USMC); in the past, the same aircraft has seldom been used by the three services (e.g. the F-4 and A-7). The production of the order of 2000 being quoted, suggests that JSF is the only fighter the United States will be able to afford in large numbers, if the cost target of about US$ 30-40 million can be met. It is unlikely that this cost target can be achieved, without some compromise on stealth (e.g. frontal vs. all aspect stealth), as a comparison with F-22 or F-117 costs might indicate. The JSF is the only potential future V/STOL fighter, as a successor to the Harrier/AV-8, since Soviet developments in that area have ceased. The prospect is that in the future the USAF will operate just two fighter types (F-22 and JSF), the USN also two (F-18 and JSF) and the USMC only one (as a replacement for both the AV-8B and F-18 C/D). The prospect of the Air Force with a single fighter type, has logistics and cost attractions, but raises a difficult issue: the grounding of that type, due to some kind of technical problem, would leave the whole air force inoperative.

1.2.3. Other Countries

The financial difficulties of Russia, following the collapse of the Soviet Union, have led to only one out of four fighter programmes surviving: the shipboard supersonic V/STOL programme was cancelled, the production of the Mig-29 and Mig-31 for the Russian Air Force has ceased, and thus the Flanker, in various versions, will fulfil all missions including viz., besides air combat, the new one of carrier-borne fighter, and the replacement of the Su-24 Fencer for long-range interdiction. The halting of development of the Mikoyan 1.42 confirms that Russia cannot afford an aircraft comparable to the F-22, and it remains to be seen if MIG proposals for a smaller, single-engine stealth fighter can be effectively supported. If Russia fails to develop a next-generation fighter, it will not be for lack of technical expertise, but rather due to limited financial resources.

As an indication of these limitations, the development of the Flanker with thrust-vectoring nozzles, i.e. thrust-vector control (TVC) integrated with the flight-by-wire (FBW) system, is being financed from the sale of production rights (of up to 200 aircraft) to China and also to India. Thus the Russian aerospace industry seems to be putting short-term survival first, at the risk of creating an export competitor and military rival, if the Chinese sell Flanker copies, the way the old Soviet Union made unauthorised copies. The next generation will show if the Chinese, starting at a lower technological level, but with a better economy, and a large, low-cost workforce, will leave Russia behind; as in the proverbial Hare and Tortoise Race, with the difference that, in this case, the Hare is helping the Tortoise to go faster. Giving the apparent lack-of-scruples of Chinese arms exports, the emergence of a state-of-the-art fighter technology, could affect both global and regional power projection, and proliferation of advanced weapons to rogue states and areas of tension.

There is evidence that China is trying to catch-up on fighter technology by producing and developing at least four generations (see Table I on p.7) simultaneously:

(i) the A-5 Fantan ground attack fighter, which is a derivative of the Mig-19, and hence a generation III fighter, is still in production, and is also exported;

(ii) also in production and being exported are various F-7 derivatives, which improve on the original Mig-21 limitations, by using double delta wing, longer fuselage with larger fuel capacity, but are still generation IV designs;

(iii) the recent first flight of the F-8 Finback, inspired on the Mig 'Flipper' prototype of the 70s, could have F-4 like intercept performance, and represents a first generation V fighter;

(iv) the FC-10, under development with Israeli assistance, embodies 'Lavi' technology, and should compare with the F-16, or generation VI.

There is only one more generation, VII or stealth fighter, about which there is no publicly known development programme. Given China's undemocratic regime, support of dictatorships elsewhere and unscrupulous export policies, these developments should not be overlooked.

The state-of-the-art fighters, like the F-22, EF 2000 and Rafale, are affordable only to the larger western nations, like the United States, France, Britain, Germany, Italy and Spain, and even then not in the numbers originally sought. With the exception of some oil-rich states, they are beyond the means of most other nations. Thus, for the many operators of F-16/F-18 class aircraft, including the smaller NATO countries, the only potential replacement is JSF, if it achieves the projected unit costs. It must be admitted that cost projections made at such an early stage in a programme have seldom been met by the production aircraft; yet, if JSF unit costs exceed about US$ 50 million, it is unlikely to be procured in the numbers US forces say they need, or to provide an affordable replacement for the many operators of F-16/F-18 world-wide.

It is ironical that, it is at the stage when fighter development reaches the limits of affordability, that technology offers a wider-than-ever range of advances. A review of current and emerging technologies, relevant to aircraft design, is the main purpose of the present work, and must precede a discussion of trends for the future, in the conclusion.

2. TRENDS IN OPERATIONAL REQUIREMENTS

The identification of the most promising technologies for cost-effective combat aircraft design, must start with an outline of the main requirements as they relate to present and foreseeable mission scenarios.

2.1. Establishing Air Superiority

Control of the air space, permanently over friendly territory to defeat enemy incursions, and temporarily over enemy areas to enable effective strikes, has always been a priority for air warfare. It translates simply in having a superior technology to ensure an exchange ratio sufficiently favourable to defeat the enemy at an early stage.

2.2. Effective Strike Missions

An effective strike mission requires success in each of a sequence of operations: penetration of hostile airspace, survival of enemy defences, target identification and assignment, firing of accurate weapons, successful remote or autonomous delivery, and safe escape and return. Much more is involved than just the design of a strike aircraft, its weapons and mission systems.

2.3. Electronic Support Aircraft

In order for a strike mission to be effective and survivable, against an enemy equipped with modern weapons, electronic support aircraft may be needed, for target identification, tracking and hand-over (e.g. J-STARS), for command, and control of defensive and offensive forces (e.g. AWACS), for jamming (ESM) and defence suppression (SEAD), and also for battle damage assessment. Timely coordination of aeronautical and space surveillance assets is essential, with very short reaction times for missions such as hunting TBM (Tactical Ballistic Missiles). There are cases, like surprise attack, when electronic support is not needed, and may even be undesirable, because jamming is a warning of potential attack.

2.4. Reduced Tolerance to Casualties

The unprecedented success and high kill ratio achieved in the Gulf War has created the expectation of similar successes in the future, with very low levels of casualties. Also the mistreatment of prisoners is displayed by rogue regimes, and covered in the press, not so much as evidence of their brutality and disrespect for the Geneva Convention, but rather as a deterrent to such abuse.

2.5. Minimisation of Collateral Damage

In the past, military campaigns sought success without much regard to casualties among non-combatants, e.g. the massive bombings of cities during the second World War were largely aimed at civilians. Nowadays collateral damage is exposed as an abuse of force, even when military targets were deliberately placed in the midst of populated areas.

2.6. Proliferation of Advanced Weapons

Technological advances have made possible smaller, cheaper and more effective weapons, produced by a larger number of states, some of which have few scruples about earning foreign currency by indiscriminate or dubious exports, because these are often better paid and enter less competitive markets than more legitimate activities. It must be assumed that such weapons as shoulder-fired surface-to-air missiles may be available to the adversary, even if it is no more than a guerrilla faction or a militia in a civil war.

2.7. Weapons of Mass Destruction

For a rogue state with considerable financial resources, a moderately advanced technology and a less than scrupulous leadership, the temptation of weapons of mass destruction may become the first national priority. Even if nuclear proliferation can be contained, chemical and biological weapons are easier to produce covertly, and ethics or international treaties have not always prevented their use.

2.8. Long-Range and Remote-Site Operations

An implicit assumption during the Cold War was that the weapon system which could defeat the technologically most advanced enemy, could also perform every other conceivable mission. The end to the Cold War has also poured cold water on such oversimplifications: long-range operations pose logistics and support problems unknown to the European scenario, transport and air-refuelling assets may not keep up with demand.

2.9. Civil Wars and Terrorism

In the classical war scenario the 'enemy' had an army holding a hostile territory, so that the mission was easy to define, even though it might be difficult to accomplish. In the case of 'diffuse' conflicts like civil wars or terrorism, the warring factions may be not separable, and the 'enemy' may be hard to distinguish from the innocent population.

2.10. Peacekeeping and Peacemaking Against all Odds

The Cold War period was one with no direct wars between superpowers, but several local, regional and civil wars, in which the superpowers took sides, and sometimes fostered rather than quenched the conflict. Peacekeeping or peacemaking is a much more noble and harder task: being friendly to all mutual enemies and remaining firm against all abuses.

2.11. More Requirements, with less Resources and fewer Systems

This wider variety of missions is supposed to be performed with increased constraints, using fewer weapon systems, developed and maintained with a smaller budget. Some critical decisions have to be taken on what, within a given defence budget, should be discarded, retained, upgraded, developed or replaced.

2.12. Some Critical Decisions or Options

The preceding decision depends on what benefits new technology can bring and at what cost:

- if the present weapon system (WS) is ineffective, and effective replacement is not feasible or not affordable, it should be discarded;
- if the present WS remains effective, with moderate support cost, and no promise of cost-effective improvement, continued unmodified operation is the solution;
- if the present WS has limitations which can be overcome by upgrades with moderate cost, then modification is the solution;
- new developments, replacements and deployments are thus limited to priority requirements, where new technology is necessary, feasible and affordable.

3. THE TECHNOLOGY CONTRIBUTIONS

This leads to a review or emerging technologies, as they may contribute to a cost-effective implementation of new or upgraded weapon systems meeting the requirements outlined before.

Before proceeding to consider each of the sectorial technologies, it is worthwhile to review (Table I) how they evolved in parallel for the seven post-war generations of jet fighters, noting the main aerodynamic, propulsion and control advances included in each of them:

(i) The first jet fighters, with unswept wings, like their piston engined ancestors, were limited to M = 0.8 by compressibility effects; early jet engines, with centrifugal compressors, and hence large frontal area, added to the drag, which did not help performance;

(ii) The use of moderately swept wings, in the second generation, delayed compressibility effects to about Mach 0.92, which was attainable with higher thrust engines, with small frontal area, due to the use of axial compressors;

(iii) The first supersonic fighters used highly swept or delta wings, and fuselage area ruling to reduce wave drag, but still higher thrusts were needed, with 20-30% augmentation through the use of afterburning;

(iv) The bi-sonic fighter generation used wings with thickness-to-chord ratio not exceeding 5%, and axial flow turbojets with up to 50% thrust augmentation through the use of afterburning;

(v) The next generation was sub-divided into three families of aircraft, seeking either (Va) multi-role capability, or (Vb) speeds beyond the heat barrier up to about Mach 3, or (Vc) very long range with significant payload;

(vi) The current high-manoeuvrability fighters use greater engine thrust not to increase speed, but rather to sustain higher performance in turning flight, and can be sub-divided into stable (VIa) and statically-unstable (VIb) aircraft;

(vii) The 'next' generation emphasises supersonic cruise (VIIa), which is most effective combined with stealth (VIIb).

3.1. Aerodynamics

Aerodynamics has always played a major role in improving the flight performance of aircraft. The areas of greater potential interest include: high angle-of-attack manoeuvres, post-stall flight, supersonic cruise, laminar flow technology, and stealth, besides several forms of vortex flow control.

TABLE I - POST-WAR JET FIGHTER GENERATIONS

GENE-RATION	EXAMPLES US RUSSIA BRITAIN FRANCE SWEDEN	MAXIMUM MACH-NUMBER	AERODYNAMICS OF WING	JET ENGINE	THRUST (ton)	CONTROL & STABILITY
I	F-80 Yak-23 Vampire Ouragan Saab 21	0.8	unswept wing	turbojet-centrifugal or axial compressor	2 t.	Boosted Mechanical Stable
II	F-86 Mig-15 Hunter Mystère Tunnan	0.92	wing swept at 35°	Turbojet with axial compressor	3 t.	Boosted Mechanical Stable
III	F-100 Mig-19 Javelin Super Mystère Lansen	0.95 - 1.3	wing swept at 45°	turbojet with fterburning (AB)	4 t. without AB 5 t. with AB	Boosted Mechanical Stable
IV	F-104/105/106 Mig-21/Su-7 Lightning Mirage III/V Draken	2.0 - 2.4	delta or thin unswept or swept at 55°	turbojet with AB	4-5 t. without AB 6-8 t. with AB	Boosted Mechanical Stable + SAS
Va	F-4 Mig-27 - Mirage F.1 Viggen	2.0 - 2.4	delta, swept or swing-wing	low by-pass ratio turbofan or turbojet	5-8 t. without AB 8-12 t. with AB	Boosted Mechanical Stable + SAS
Vb	A-11/SR-71/YF-12 Mig-25/31 - - -	3.0 - 3.3	delta or swept	turbojet	12-14 t. with AB	Boosted Mechanical Stable + RSS
Vc	F-111/F-14 Su - 24 Tornado - -	2.0 - 2.4	swing-wing	turbofan	4-6 t. without AB 7-9 t. with AB	Boosted Mechanical SAS
VIa	F-15 Su-27/Mig-29 - - -	2.0 - 2.4	delta -canard or swept	low by-pass ratio turbofan	5-8 t. without AB 8-12 t. with AB	Boosted Mechanical Stable + SAS
VIb	F-16/F-18 - - Mirage 2000 Gripen	2.0 - 2.4	delta -canard or swept	low by-pass ratio turbofan	5-8 t. without AB 8-12 t. with AB	FBW RSS
VIIa	- - Eurofighter Rafale -	2.0 - 2.4	limited stealth	supersonic cruise turbofan	5 t. without AB 8 t. with AB	FBW RSS
VIIb	F-22 1.42 - - -	2.0 - 2.4	stealthy wing-body blending	supersonic cruise turbofan	12 t. without AB 17 t. with AB	FBW RSS

SAS - Stability Augmentation System
FBW - Fly-By-Wire
RSS - Relaxed Static Stability

3.1.1. High Angle-of-Attack Manoeuvres

The ability of an aircraft to out-manoeuvre another in air combat, depends on flight at high angle-of-attack, to achieve high lift and high instantaneous turn rate. A high-sustained turn rate will require, in addition, high thrust, to overcome drag. Whilst aerodynamic performance in high angle-of-attack flight is a contributor to combat agility, it is not the only one. A target cueing system, such as an helmet-mounted sight, with large off-boresight capability, allows target engagement, with less nose pointing; provided, of course, that the air-to-air weapon, e.g. a short range missile, has sufficient agility, through aerodynamic or thrust-vector control (i.e. deflected exhaust), to intercept a target at a large off-boresight angle. Thus the key to high combat agility lies in a good blend of aircraft aerodynamic performance, target cueing systems and air-to-air missile capability, which avoids costly overemphasis on just one of the elements. High angle-of-attack flight capability is enhanced by thrust vectoring nozzles, which are also relevant to post-stall control.

3.1.2. The Use of Post-Stall Control

Post-stall control (PST) has been the subject of the X-31 demonstrator programme. Simulation of one-on-one air combat have given PST high marks, and recent flight tests of the X-31 vs. the F-18, F-16 and F-14, have produced even more impressive scores:

- starting from a favourable position, the PST aircraft gives its opponent no chance to escape;
- starting from an equal position, it gains advantage in an overwhelming majority of cases;
- starting from inferiority, it can regain advantage in some cases.

What demonstrations have also showed, and should be tested in flight, is that PST rapidly loses its benefits in multiple engagements. An aircraft which uses PST loses energy, and becomes a 'sitting duck' for several seconds. In fact PST has several antecedents, which may be worth recalling briefly. Perhaps the oldest precedent, was the use in the first World War, of stall by biplanes like the Fokker D.VIII: the pilot would initiate a climb, stall the aircraft, and dive into the back of its opponent. This was possible due to the docile, controllable and spin-free stall of this aircraft. The 'black death' of Argentinean Mirages in the Falklands conflict, was a similar, in that the Harrier decelerated using thrust vectoring, to gain a missile kill position. This tactic might not have worked so well, if the Argentineans had tried to take advantage of the low energy state of their opponent.

One of the most interesting issues concerning extended PST flight, or decoupled control modes, concerns the potential for pilot disorientation. The pilot is used to assuming that the aircraft flies where the nose is pointing, or thereabouts, to within a moderate combination of sideslip and angle-of-attack. However, after some time at high angle-of-attack and sidelip, it becomes difficult for the pilot to know what the velocity vector is doing relative to the attitude vector. Extended PST flight or extensive use of decoupled control modes, may imply the need for special displays, to show the pilot his velocity vector and also the location of opponents. A pilot who does not know his velocity vector, cannot have good situational awareness in air combat.

3.1.3. Supersonic Cruise

An option to some extent opposite to post-stall control, with its low energy state, is to maintain a high energy state, through supersonic cruise. Supersonic cruise requires an engine with high thrust and low fuel consumption, i.e. military thrust (without afterburning) must de sufficient to maintain supersonic flight. This becomes feasible with the new generation of jet engines with high thrust-to-weight ratio; as the latter parameter continues to increase, with advances in jet engine technology, supersonic cruise becomes easier to achieve.

Supersonic cruise is particularity effective in air combat, when combined with stealth and beyond-visual-range (BVR) air-to-air missiles (AAM):

- stealth allows the aircraft to approach the target undetected, up to missile launch;
- as the fire and forget BVR AAM homes on the target the aircraft flies away, still undetected;
- by maintaining supersonic cruise, several engagements can be flown, with higher probability of survival.

Supersonic cruise is also of use in ground attack or deep interdiction missions, by reducing the time the aircraft is exposed to air defences.

3.1.4. Aerodynamics of Control

Both post-stall flight and supersonic cruise pose aerodynamic issues which affect flight control. A post-stall control (PST) requires careful integration with the flight control system (FCS) of the aircraft. In particular, flight at high angles-of-attack may generated large yawing moments, due to asymmetric vortex shedding; at low speeds, the control surfaces will lack the necessary control authority, so that the problem must be solved at the aerodynamic design stage, and cannot be left to the FCS design. Directional and lateral stability are also issues for supersonic manoeuvre, when the location of airbrakes becomes critical, and changes in load factor and trim condition have to be accommodated quickly by the FCS. In particular, the combination of supercruise and stealth implies particular control and aerodynamic requirements, since minimising the radar cross-section (RCS) and the infra-red signature limits the aircraft attitudes relative to 'enemy' sensors.

3.1.5. Aerodynamics of Stealth Configurations

The external shape of aircraft has traditionally been determined by aerodynamic considerations, coupled with requirements for available internal volume, efficient structural design and effective control surfaces. The advent of stealth has brought aircraft shapes which would never have been considered on aerodynamic, structural or control grounds alone. For example, the F-117 uses multiple flat facets, with the risk of flow separation at the edges. The reason for the flat facets was that at the time F-117 was designed, computers were able to solve Maxwell's equations only for flat surfaces. With increases in computer capability, it became possible to solve Maxwell's equations for smooth, curved surfaces, as used in the F-22 and B-2. All of these stealth aircraft pose unconventional control problems, e.g. the B-2, which is subsonic, lacks vertical control surfaces. The F-22, which is supersonic, has canted fins. The F-117 also does, although it is subsonic like the B-2, because at the time it was designed, control technology was not sufficiently advanced to dispense with fins. The wing-body blending typical of recent stealth aircraft, while less radical than the flat facets of the F-117, still poses aerodynamics and control challenges.

3.1.6. Laminar Flow Technology

A laminar flow (LF) wing achieves a lower drag, and hence requires less thrust, implying a lower fuel consumption. It also achieves a higher lift-to-drag ratio which, in cruise condition, improves range and endurance, allowing long distance deployment without, or with fewer, air refuellings. Laminar flow is achieved naturally (i.e. without suction), over the whole of the wing, at very low speeds, e.g. for sailplanes. At high subsonic cruise speeds, flow separation towards the trailing edge must be prevented, by sucking the boundary layer through tiny holes in the wing. Achieving laminar flow in supersonic flight is more difficult, but still possible. The potential of the laminar flow wing, or engine nacelle, to improve aircraft aerodynamics and performance, has been recognised for over half-a-century. Its practical exploitation has been prevented by problems of contamination (e.g. clogging of the air suction holes by dust and particles), and by the power requirements and systems needed for boundary layer suction. Laminar flow technology is likely to be applied first to civil transport aircraft, for which the benefit is greater in terms of longer range and lower fuel consumption, and the operating environment is more benign.

3.1.7. Forebody Vortex Control (FVC)

The flow over an aircraft at high AOA is dominated by the presence and buffeting of forebody vortices. A suitable management of these vortices can result in very large lateral reactions on the forebody. The vortices can be manipulated by pneumatic means (suction or jet blowing near the nose, slot blowing) or mechanical arrangements (deployable or movable forebody strakes, rotatable miniature nose-tip or nose-boom strakes). One novel concept to be explored consists of high-frequency alternative blowing on the two sides of the forebody, with the lateral reactions controlled by the duty cycle of the pulsation. This would obviate the need to first make the flow symmetric (e.g. by small strakes) before introducing the desired flow asymmetry (e.g. by canted blowing). Although at the present time the development of FVC is lagging behind thrust vectoring, in a decade or two both can be expected (possibly together) to be available on operational aircraft.

3.1.8. Control of Leading-Edge Vortices

Slot blowing (or suction) near swept wing leading edges can induce large rolling moments. It will be possible to minimise wing rock by appropriate pulsation of blowing on the two sides of the wings. A novel concept, presently under very early stage of development, is the control of LE vortices by sensor-actuator-processor systems based on micro-electromechanical (MEMs) cells near and around leading edges. These devices would modify LE vortices in an early stage of their formation, making the process very efficient.

3.1.9. Dynamic Lift

High-rate pitch-up motions at high AOA (such as in the "Herbst" or "Cobra" manoeuvres) cause the flow response, and in particular the motion of the vortex breakdown location, to lag considerably behind the motion of the aircraft (or wing). This can result in large increases in the instantaneous lift ("dynamic lift") and pitching moment. If these effects can be harnessed, e.g. by artificially increasing the persistence of the pertinent instantaneous flow structures, considerable gains in dynamic lift and therefore in instantaneous turn rate and agility could be realised.

3.1.10. Other Aerodynamics Enhancements

The preceding three techniques involve some form of vortex control, to improve aerodynamics and agility at high angle-of-attack. Another contributor to agility at high-angle-of-attack is thrust vectoring, which is achieved normally by mechanical means: paddles in the jet exhaust or deflection of nozzle flaps; the latter cause less of a thrust loss. A possible novel concept is the introduction of fluidic vectoring, by means of a suitable counter-flow on one side of the nozzle, to replace mechanical flow deflectors.

The use of thrust vectoring (and, at high angle-of-attack, also the use of forebody vortex control) could in the future permit removal or reduction in size of the vertical tail, with considerable pay-offs in reduced zero-lift drag, weight and radar cross-section. Some existing subsonic aircraft, even without thrust-vectoring, e.g. the B-2, already dispense with vertical tails.

Another possibility to increase agility, which is not limited to high angle-of-attack, is to have movable canards, together with suitable leading-edge extensions. In the past, the Saab 37 Viggen had a fixed canard with blowing, to avoid flow separation ahead of the wing.

3.2. Propulsion

Advances in propulsion, together with those in aerodynamics, have played a major role in increasing the performance of successive generations of combat aircraft. The most important improvements in the timeframe 2020, are likely to be higher thrust-to-weight (to-volume and to-frontal area) ratio, variable cycle, reduced fuel consumption, two-axis thrust vectoring and lower acquisition and maintenance costs.

3.2.1. Evolution of Propulsion Technology

Table I shows the role played, in successive fighter generations, by increased thrust and reduced fuel consumption, sometimes obtained without increase in engine size or weight.

3.2.2. The Single-Engine Multi-Role Aircraft

Over the timeframe to 2020, we may expect engine thrust-to-weight ratios from 15 to 25:1, i.e. 15 - 25 ton compact engines should be available. This will allow the design of a single-engine fighter with sufficient payload-range to accomplish most missions, and having supersonic cruise as an added bonus.

3.2.3. Specific Fuel Consumption

Reductions in specific fuel consumption (SFC) of 20 to 35% in the 2020 timeframe are important, in that they will compensate for the increased engine thrust, leading to a comparable total fuel consumption. Thus the payload increase made possible by the higher thrust translates mostly into a greater weapon load or extra fuel to increase range and endurance. Increased endurance is important in missions such as combat air patrol, to control airspace for extended periods of time, with a minimum number of sorties. Increased payload-range is beneficial in strikes against targets remote from well equipped airfields, and lessens the need for in-flight refuelling.

3.2.4. Two-Axis Thrust Vectoring

Thrust vectoring has multiple benefits, in terms of higher agility, better high angle-of-attack performance and post-stall control. The current one-dimensional, or axisymmetric nozzles, or paddle-type thrust deflectors, should give way to two-dimensional nozzles, allowing thrust vectoring both in pitch and yaw, at fast rates, and with minimal thrust losses. The full exploitation of the potential of two-dimensional thrust vectoring over a hemispherical region some 20-

30° around the aircraft longitudinal axis, will require an increased integration of aerodynamics, propulsion and flight control; this can also be exploited for fire control, in air-to-air combat, as well as ground attack modes.

3.2.5. The Variable-Cycle Engine

Pushing engine technology further, the variable-cycle engine allows optimisation at more than one design point, e.g. having an engine which is close to optimal both for long-range cruise and supersonic dash. The added complexity of the variable cycle engine will have to buy its way through improved performance. It may be that technology will be more effectively used in the short term to improve the traditional single-cycle engine, although the variable cycle will probably prevail.

3.2.6. Improvements in Engine Components

The improvements in thrust-to-weight ratio, thrust-to-volume ratio, thrust-to-frontal area ratio, thrust-to-airflow ratio, and in specific fuel consumption, will come from better design of the whole range of major engine components, e.g.:

- Achieving higher compression ratios with fewer stages;
- More efficient combustor design;
- Higher turbine entry temperatures, implying better blade cooling;
- Use of more advanced materials, including composites or ceramics in hot sections;
- Design and operation to closer tolerances;
- Reduction in weight of components, e.g. replacing conventional rotors with disks and blades, by hollow disks (blisks), or rings (blings) with blades;
- Reduced parts count.

These detailed design improvements in critical areas and components can offer not only the performance benefits already mentioned, but also reductions in cost of ownership of 20 to 60% by 2020.

3.2.7. Lower Acquisition and Operating Costs

As engine cost has been increasing with greater sophistication, some limit in this growth is needed. It should be borne in mind that a jet engine is a high maintenance item, and that a higher acquisition cost may be compensated by smaller spares inventory, less man-hours of work and reduced downtime. Similarly, a larger investment in research and development may well pay-off in increased performance and reduced fuel consumption. The latter alone is a major factor in operating cost.

3.3. Flight Dynamics and Control

Modern high-authority digital flight control systems are essential to the effectiveness of current highly manoeuvrable fighters, and may find their way into the next generation of helicopters. This development has not been without problems, most notably PIO (Pilot Induced Oscillation), which remains a partially unresolved issue.

3.3.1. Active Control Technology

There are several reasons why advanced high-authority digital control is an essential feature of modern aircraft design:

- it can give good handling qualities in a flight envelope more extensive than for previous generations of aircraft (when instructors want to demonstrate a hard-to-fly aircraft nowadays, they need to go to the century series fighters);
- it can disguise or make flyable undesirable aerodynamic features;
- it can provide carefree handling in significant portions of the flight envelope;
- it can provide protection against spin, or other forms of departure from controlled flight;
- it can reduce the workload of the pilot in flying the aircraft, and allow him to concentrate on the mission;

- it can automate important functions, such as navigation, fire control, terrain avoidance;
- using gust alleviation, it can increase low-level penetration speeds;
- using active structural control, it allows a smaller aircraft to perform the same mission;
- by implementing negative stability, a smaller wing, powerplant, fuel load, etc. will give, for the same mission, greater cost-effectiveness;
- it gives the opportunity for generalised integrated control, of flight, propulsion, fire control, and structure.

The topics in the preceding list are not mutually exclusive, and they do overlap partially; furthermore, the list is not exhaustive. But it gives some of the many reasons why advanced control is a major contributor to progress in aviation.

In this world few worthwhile things come for free, and advanced control has a price. It solves many problems, but also creates a few others, most notably the PIO. Before proceeding to consider PIOs, the benefits of extending modern control technology to helicopters are reviewed. The precursors are the European NH90 medium helicopter, which uses fly-by-wire, and the US Comanche scout helicopter, which uses fly-by-light.

3.3.2. Requirements for Helicopter Flight Control

The fundamental requirement of an helicopter flight control system is that it should enable the pilot to achieve the intended mission safely and with minimum workload. This implies that it should endow the vehicle with adequate stability, crisp primary responses and minimum cross coupling, along with automatic control modes aimed specifically at reducing the pilot's control activity. Further requirements naturally include high integrity, low weight, low life-cycle costs, high reliability, and ease of maintenance.

Up to the present day, the flight control systems of all production helicopters have been based on mechanical linkages between the pilot's inceptors (sticks and pedals) and the rotor controls. In most modern military helicopters, this mechanical system is augmented by an automatic flight control system (AFCS). The AFCS operates to stabilise the inherently unstable vehicle, reduce undemanded motion such as that due to cross-coupling and turbulence, and also has various autopilot modes such as altitude, speed and heading holds. This AFCS is implemented as an analogue or digital electronic system and operates with limited authority of total control, so that ultimately the pilot retains the capability to override the system in the event of failures.

This type of flight control system has been used for many years with great success. The latest AFCSs incorporate digital processing and multiplexed architectures to provide a wide range of mission related autopilot modes, high mission reliability and a high level of safety.

In many military helicopter operations, mission requirements are becoming more demanding through the need to operate in more severe operating environments and a greater emphasis on flying lower and faster to avoid detection and engagement. In such operations, the helicopter is currently limited not so much by inherent performance limitations, but by the level of pilot skill and workload required to fly the vehicle close to these limits. In terms of enhancing helicopter agility much of the emphasis is therefore on improving the pilot's ability to use the full capability of the vehicle with acceptable workload.

Existing helicopter flight control systems suffer various weaknesses here. In aggressive manoeuvring flight they can saturate, causing loss of stabilisation and a step change in the response characteristics of the vehicle, thus greatly increasing pilot workload. Existing systems also provide minimal cues to the pilot of an approach to limits. Thus the pilot is forced to fly less aggressively so as to allow him to monitor head-down instruments or, if maintaining eyes-out is essential, he must fly very conservatively to ensure that limits are not approached.

3.3.3. Benefits of Fly-By-Wire/Light Systems

For military helicopters in the 2020 timeframe, a radical change to flight control systems can be expected with the introduction of fly-by-wire/light systems with enhanced authority control laws. These systems will have electrical/optical signalling replacing the mechanical linkages and extended authority control laws so that full flight envelope manoeuvre command control system strategies can be introduced. Such systems are expected to give benefits in terms of weight, reliability, maintainability, vulnerability and life-cycle costs, and will allow improved structural and ergonomic design. However, the major anticipated benefit will be to handling qualities. Primary responses will be consistent throughout the flight envelope with minimal cross coupling, even in aggressive manoeuvring flight. It will be possible to tailor the control laws for different missions and mission phases, providing different response types and characteristics to ensure optimum performance and minimum workload at all times and for all conditions. Response types which are envisaged include rate demand, attitude demand and translational rate (or velocity) demand. Rate demand systems are seen as the most appropriate for aggressive manoeuvring in good visual conditions; attitude demand is seen as more appropriate for precision flying particularly at low speeds and in poor visual conditions. Translational rate command requires more sophisticated sensors, but is expected to give further benefits for precision manoeuvring in poor visual conditions.

Carefree handling systems aim to help the pilot to respect his vehicle's limits and to improve his ability to use the full performance of the helicopter while minimising pilot workload. Features might include head-up visual, audible and tactile warnings and direct intervention systems which act directly through the flight control system to ensure that the pilot cannot stray inadvertently beyond the vehicle's flight envelope limits. The ultimate benefits in terms of handling qualities, performance and workload can be expected from the integration of carefree handling features with the high authority fly-by-wire/light systems and manoeuvre demand strategies described above.

3.3.4. Open Issues to be Resolved

The introduction of the new flight control technologies described above requires careful consideration of man-machine interface issues. Fly-by-wire/light offers much greater design freedom in the cockpit, through removal of the mechanical system constraints, leading to the adoption of more ergonomically efficient layouts with side-arm inceptors replacing the conventional large displacement sticks and pedals. The success of the new flight control systems will be critically dependent on establishing appropriate inceptor geometries and force displacement characteristics, and on integration of the various control modes with suitable (probably helmet-mounted) displays.

The trend towards more advanced helicopter flight control systems and manoeuvre demand strategies has led to development of new requirements for helicopter handling qualities. The United States has been prominent in generating these new requirements, resulting in an Aeronautical Design Standard, (ADS-33D, "Handling Qualities Requirement for Military Rotorcraft", July 1994), but further work has also been done in this field in Europe and Canada. These requirements identify critical mission task elements (MTE) for evaluating helicopter handling qualities, identify the required response types for the different MTEs in varying "usable due environments" (operating conditions), and define the required response characteristics for each response type. The requirements are far from complete at present, substantial further work being required to define response characteristics for translational rate command systems, cross-coupling requirements, heave axis response requirements and sidestick controller characteristics.

Helicopters, as well as aircraft, have been shown to have PIOs, and this is one of the issues which deserves further consideration.

3.3.5. Some Cases of PIOs

The term "Pilot Induced Oscillation" (PIO) is to some extent a misnomer, if it implies some pilot responsibility in the event; it could also be a Probably Inevitable Oscillation, since it is as much task driven as pilot induced. The PIO is a violent oscillation, which arises in the control system of the aircraft, as a sequel to aggressive pilot inputs, typically in high gain tasks, like precision landing and air-to-air tracking. The PIO came with the new generation of highly augmented aircraft and spacecraft, e.g. the F-16 had some PIO tendencies on landing, and one of the Space Shuttles had a wing rock PIO on landing at Edwards which was survivable.

The PIO problem has been an undesirable feature of some aircraft designs for two decades, and it was at first ascribed to excessive time delays in the control system, allowing oscillations to get out of hand. It was prescribed that a time delay of no longer than 120 ms should apply to the entire control loop, from pilot input to control surface movement, including every computation and motion in the process. While this did help the situation, it did not eliminate the problem: the F-22 had one PIO accident and the Saab Gripen two, just to name more recent, much publicised, cases.

3.3.6. Causes and Cures of PIOs

There is not, in the published literature, any method which is claimed to lead to PIO-free design. Thus the PIO cannot be likened to a curable disease like flu, for which the medicine is known, but is more like cancer: we know what is associated with it, but not the final cause or unfailing cure. The PIO is always associated with a high gain task, where the pilot controls aggressively the aircraft, and puts in wide bandwidth inputs. In the same situation, an aggressive pilot is more likely to excite a PIO, than a relaxed hands-off pilot, who does not attempt precise control but only general stabilisation. In this respect it has been noted that both Gripen PIO accidents occurred with the same pilot, who possibly has a high-gain approach to piloting technique.

The cure to a PIO is to design the control system of the aircraft in such a way that it cannot be excited by any likely pilot input. This is much easier to say than to implement. PIOs are sought in flight simulators and sometimes found, and cured. Other PIOs appear in flight, and in most cases, can be reproduced back in the simulator. But, as with spins, there is no sure method of finding all PIOs and cures for them. The analogy with spin is appropriate, since a PIO can turn into a non-linear phenomenon, if actuator deflection or rate limits are attained. A partial safeguard or precaution against PIOs is to provide ample control power, large surfaces, large maximum deflections, and high maximum actuator rates and accelerations.

3.3.7. The Control System Gurus

The fact that there are no methods to find all PIOs or to ensure that they do not occur, has created a situation in which well-to-do consultants or control systems gurus thrive. In some respects it resembles medieval science. The reason science did not progress in medieval times was that the methods were not disclosed: the problems were put, often as public challenges, and the solutions presented, but the methods were hidden, so no progress was made. If PIO consultants have a cure to PIOs, they don't give it away. Typical explanations are that: the understanding of a PIO requires a pilot model and an aircraft model; the aircraft alone has no PIOs, and it is only a particular kind of pilot input which causes it. Yet, an unmanned aircraft, the Lockheed-Martin DarkStar, has had a PIO accident - sometimes referred to as a CIO (Computer Induced Oscillation). It is also stated that there is no simple classification, since PIOs can be linear or non-linear, in any control axis, etc.

3.3.8. Some Current Programmes

Some of the perplexities of the current situation can be illustrated by some examples and questions.

The Rafale and Eurofighter are comparable, at least in the general configuration (delta canard) and control technology (quadruplex fly-by-wire). The Rafale exceeded Mach 1 on the first flight, and attained Mach 1,8 on the third flight. The first flight of Eurofighter was delayed two years because of flight control system software concerns, and in the first flight the aircraft did not retract the undercarriage. Was Dassault cavalier in the first flights of Rafale, or were the Eurofighter partners too cautious?

There has been little public mention of PIO problems with the Rafale, or with its fly-by-wire predecessor, the Mirage 2000. Are Dassault fighters immune to PIOs? Or have they occurred and not been reported?

It has been stated that, by the time Eurofighter enters in service, in 2002 or beyond, not all flight control modes will have been cleared. The stage has been reached where validation of flight control software takes longer than anything else in an aircraft development programme.

An old edge was "don't develop the aircraft and the engine at the same time". The Eurofighter partners thought the Eurojet EJ-200 was going to be the programme pacer. It isn't; the flight control system is.

We have chosen the Eurofighter as example, but it would be unfair to overstress that example. At least none has been lost so far, which is better than can be said of other programmes, and justifies the caution of the developers.

It should be borne in mind that not only flight control systems, but all software-intensive systems, tend to exceed development schedules and budgets; part of the PIO problem may lie in the difficult area of software validation and verification. But it has not been proven that it is solely a software problem, and some flight dynamical, aerodynamic or control issue may be involved.

In conclusion, the PIO has become a potent programme disruption issue:

- flight control system validation can take longer than any other task;
- PIOs cause programmes delays and increased costs;
- until cleared, they cause operational limitations.

A company which, alone, had the solution of the PIO problem, would see its competitors lag behind on schedule and cost. More important, the modern PIO seems to have joined the traditional spin, as the two main limitations on flight dynamics. Both problems deserve a serious research effort, to minimise their effects on aircraft development times and the lifetime limitations on their operation.

3.4. Advanced Structures and Materials

Structural design will continue to benefit from advances in high-strength and/or lightweight materials; a not too distant future will see the introduction of intelligent or adaptive structures, with embedded sensors and actuators. More importantly, structural design is becoming the focus of so-called concurrent engineering, which integrates at an early design stage, all technical disciplines (aerodynamics, propulsion, control, etc.) as well as those aspects affecting life-cycle costs (production, maintenance, operations, etc.).

3.4.1. Lightweight and Composite Materials

One of the main objectives of structural design remains lightweight structures, given that weight reduction has a cascade effect in aircraft design: a reduced weight means less need for lift, hence a smaller wing, with less drag, hence an engine with less thrust and lower fuel consumption, which again reduces weight and volume. The biggest weight savings have come from the use of composites, which has gradually expanded from smaller structures (access panels, non-structural elements) to larger elements (fins, or complete wings). Composite materials give considerable flexibility in aero-elastic tailoring, by choosing the number of layers and their orientation. The delamination and fatigue properties of composites, and their protection from electric discharges like lightning, are areas where further research is needed.

3.4.2. High-Strength Materials and Structures

Larger or critical items of primary structure in the fuselage, would benefit also from the weight reduction afforded by composites, but the technology may take time to become cost-effective; reducing the cost of complex composite structures is also a priority. Conventional aluminium structures can be replaced by other lightweight metal alloys, e.g. aluminium-lithium, at a 20-30% weight saving. In areas where very high-strength is needed, titanium and similar alloys will continue to be used, but their fraction of the weight of the structure may be reduced. More exotic materials, such as boron and beryllium, will increase in use, to the extent that their cost is reduced.

3.4.3. Armour for Helicopters and Aircraft

The provision of armour for the pilot and gunner, and for some systems, is now standard for anti-tank helicopters. With a few notable exceptions of slower aircraft like the Fairchild A-10 Thunderbolt and Sukhoi Su-25 Frogfoot, airplanes tend not to protect the pilot with armour. It is clearly not going to be effective against air-to-air or surface-to-air missiles with large warheads or broad fragmentation patterns. The value of protection for strike aircraft against small arms fire and splinters has to be balanced against the weight penalty; the latter is smaller for modern composite armour, e.g. Kevlar-based.

3.4.4. Intelligent and Adaptive Structures

The term intelligent or adaptive structures is applied to materials with imbedded sensors, plus actuators which change their shape. The actuators are based on piezo-electric or similar materials, which are deflected when an electric current flows through them or an electromagnetic field is applied. The three key aspects for such structures are:

- The material should have sufficient response, i.e. allow large deflections, with moderate electric currents and power consumption;
- The cost of the piezoelectric material should not be a high fraction of the cost of basic structure;
- It should be possible to imbed the piezoelectric material in a variety of structures, without high manufacturing, support, repair and replacement costs.

Although this is a promising area, one should not underestimate the research effort needed to solve all these problems. The smart structures may find use before 2020 for selected applications.

3.4.5. Stealthy Control and Manoeuvres

Once moderately large smart structures become available, it may be possible to dispense with conventional, hinged control surfaces, and replace them by smooth deflections, e.g. ailerons replaced by wing bending, rudder by fin bending, elevator by tailplane bending. Some stabilisation surfaces, like fins, have already been eliminated from subsonic stealth designs like the B-2. The smooth bending of surfaces has advantages in stealth over deployment of hinged surfaces, e.g. a continuous camber change of a wing is preferable to extension of leading and/or trailing edge flaps.

3.4.6. De-coupled Control Modes

Smart structures can also have aerodynamic benefits, e.g. by adapting the wing section or camber to the flight regime, viz. long-range cruise or supersonic dash. Although wing shaping with mechanical actuators has been demonstrated in the F-111 prototype with Mission-Adaptative Wing (MAW), the complexity and loss of internal volume for fuel would be unacceptable in an operational design. A smart structure design would have to preserve fuel tankage, while achieving wing deformation with moderate power consumption and small increase in complexity compared to an 'inert' wing. Combining smooth surface deflection with de-coupled control modes, it becomes possible to control an aircraft in one axis, without affecting the other, e.g. a flat turn will reduce radar cross-section compared with a high-bank angle turn.

3.4.7. *Attitude and Velocity Vectors*

De-coupled modes also allow a distinction between the attitude and velocity vectors: the aircraft may be flying in one direction, and pointing the nose and firing in another direction. This is of interest in air-to-air combat, as an alternative or complement to other methods of off-boresight target engagement, such as Helmet-Mounted Sights (HMS), coupled to air-to-air missiles with wide field-of-view seekers. Fuselage pointing may be more useful still, or have less alternatives, for ground attack, by allowing an aircraft to engage, in a single pass, several targets around its velocity vector.

3.4.8. Synthesis of Design Disciplines

Smart structures used for load alleviation, aerodynamic tailoring and stealthy manoeuvring, are good examples of the integration of traditionally distinct design disciplines. In a different way an even broader integration of disciplines is involved in concurrent engineering: all contributors to life-cycle cost (LCC) are considered at the design stage. This requires the technologists (aerodynamics, propulsion, control, structures and materials), who tend to live upstream in the life-cycle, to share the design process with the implementers downstream (viz. those who manufacture, maintain *and operate the aircraft).*

3.4.9. Production Cost and Time

Concurrent engineering has allowed significant cost and time reductions in the car industry, where it was pioneered. *Its adoption by commercial airplane manufacturers, like Boeing and Airbus, promises to halve delivery times,* as well as reduce costs. The case of commercial airplane manufacture by McDonnell Douglas, with declining orderbooks, has proved that profitability can be retained, at very low production rates.

3.4.10. Low-Rate, Low-Cost, Fast Production

These lessons from the civil market should not be missed in the procurement of military aircraft, since they prove that, after all, low-rate production, low cost and fast delivery are all compatible:

- low-rate production may be imposed by reducing defence budgets and high unit costs;
- reducing production cost, and not increasing it significantly as production rate declines, may be essential to programme survival in the current financial climate;
- faster delivery will allow re-enforcement of deployed forces with less delay, when budget priorities or security perceptions change.

3.4.11. Maintenance and Operating Cost

Concurrent engineering, associated with just-in-time production, reduces spares inventories, frees factory floor space, and allows more efficient use of the work force. This is true not only in production, but also in operations, with reduced spares inventory, maintenance times and improved accessibility. It should be borne in mind that reducing manufacturing cost and reducing operating cost, may lead to different designs; in finding a compromise or priority, the objective should be reducing life-cycle cost.

3.5. Crew Stations

The man-machine interaction has become a technology of its own, with four generations of cockpit technology: electromechanical, digital, glass and remote. The aeromedical issues include not only human performance (such as workload), but also protection (e.g. against lasers) and physiological aspects (g-loads, fatigue).

3.5.1. The Electromechanical Cockpit

The first generation of electromechanical cockpits, with numerous dials and instruments displaying always the same information, looks terribly old-fashioned in this age of computer displays and screens. It is easy to forget how long it served aviation, and how big a progress was its replacement by the modern digital cockpit. The reduction of the crew of transport aircraft from 5, 4 or 3 to just 2 would not have been possible with electromechanical instruments: there would be too many of them for a two-man crew to monitor. Similarly, the multiple and complex missions of modern combat aircraft, could not be displayed to a 1 or 2 man crew, in the space available in a fighter cockpit, using electromechanical instruments.

3.5.2. The Digital Cockpit

Military pilots seem to have adapted much more readily and willingly to the digital cockpit and the associated automation, than some commercial pilots, who still resent their lack of ultimate authority in some areas. Of course it is no longer possible to give the pilot ultimate control of tasks such as stabilisation of a negative stability fighter, and it would be unwise to add this to his workload, even if it were feasible. The design of the modern digital cockpit remains, as in the past, a race or competition between three factors:

- condensing the mass of available information to a set of essentials which can be absorbed by the crew;
- giving the crew the means to manage the mission and take the decisions for which the human brain is the most flexible tool;
- finding the space to display all this data and putting all the means of interaction (inceptors, buttons, touch screens, voice commands, etc.) at the reach of the crew.

3.5.3. The Glass Cockpit

The digital cockpit represents an advance over the electromechanical instruments, in that it makes a better use of available display and interaction space, because:

- information from several instruments can be integrated in one display;
- that display can be changed according to flight condition or tactical scenario;
- any display can act as back-up to the others, in case of failure.

Concerning the last point, it should be noted that redundancy in displays may need to be backed-up by redundancy in sensors, i.e. obtaining comparable data from multiple sources.

The glass cockpit takes this flexibility one step further, towards the ultimate, by allowing all cockpit area to be used to display any information. The loss of outside view, which is the most basic human sensor, may not be taken lightly by pilots; the visual sensors would have to match or improve on the human Mk.1 eyeball in every condition, otherwise pilots might demand a direct outside view plus a sensor display.

3.5.4. The Remote Cockpit

Once the glass cockpit is proposed as the concept, it is natural to ask about the next step: have the pilot on the ground or in another vehicle, i.e. in a safer or more comfortable environment, controlling an unmanned or uninhabited vehicle. Both in the glass and remote cockpits, the pilot has no direct vision of the outside world. The glass cockpit retains more motion cues, because the pilot is in the aircraft; but having the pilot in the aircraft adds size, cost and complexity, and limits flight dynamics, so in this regard the remote cockpit is better. The major extra requirement of the remote over the glass cockpit, is that data has to be transmitted from the aircraft to the ground and back. If that data transmission problem is overcome, then the remote cockpit is preferable to a glass cockpit, and the latter may even be a missed generation. It should be borne in mind that increasing sharing of data between air vehicles, space systems and ground stations, to improve situational awareness and mission effectiveness, will be the norm in the future, for manned and unmanned aircraft.

3.5.5. Cockpit Generations

Figure 1, taken from FVP (Flight Vehicle Integration Panel) WG21 (Working Group) report "Operational Effectiveness of Glass Cockpits, AR-349", shows 5 generations of fighter cockpit design, with the second to the fourth representing sub-divisions of what we termed the "digital cockpit" (3.5.2.), according to the technology used. Since this is the current generation, a greater level of detail is appropriate. The leading technology developer tends to be the single-seat fighter cockpit, for which there is less display space available and the pilot workload is greatest. The same technologies apply to multi-crew aircraft, where the size of the crew and sharing of tasks are additional degrees-of-freedom.

3.5.6. Man-Machine Interaction

The main technologies for man-machine interaction, be it the display of information or the input of commands, are multi-function displays (MFD), head-up displays (HUDs), helmet-mounted displays (HMDs), HOTAS (hands-on-throttle-and-stick), DVI (direct voice input) and aids to situational awareness (SA).

3.5.7. Display Technologies

Improvements in MFDs include less power requirements, greater brightness (for use in daylight and against direct sunlight), less depth (to minimise panel 'volume'), use of colour (to display clearly more data). The MFDs occupy about 40% of display area in current designs, and this could increase by the removal of the HUD. The latter provides a field-of-view (FOV) of up to 25°, but partially obstructs vision. It could be replaced by HMDs, with a wide FOV (WFOV), which have advantages to cue weapons to off-boresight targets, in particular air-to-air missiles in air combat. The main progress in HMDs is to increase the total FOV (TFOV), to display more data, and to make them lighter and more comfortable to the user. HMDs have been used so far mainly in fixed-wing aircraft, and they are likely to see increasing use in helicopters.

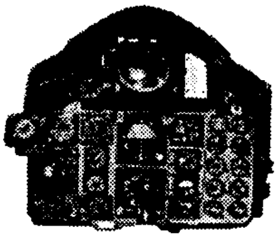
3.5.8. Data and Command Inputs

The data input is currently made by keyboards or touch screens, and many of the commands are concentrated on the throttle and stick, which may have more than 20 buttons in a current fighter. While automation of radar modes and other functions may eliminate some input needs, this can be more than outweighed by increasing system complexity and functions, requiring a greater total input of data and commands. The DVI, first extensively used in the Eurofighter, is important in extending the range of methods of man-machine interaction, beyond the visual and tactile, and into the acoustics. It represents an extension of voice warnings and audible alarms, from data output, into data input or crew commands. This has been made possible by progress in voice recognition, to accommodate variations in human voice between individuals, and for the same individual, depending on stress and other factors. As with all other means of man-machine interaction, there are additional training requirements for the crew.

3.5.9. Situational Awareness

The purpose of displays is to give the crew a good situational awareness. Given the increasing amount of information that goes into making a good assessment of a complex scenario, the interpretation task may exceed the capability of the human mind, even if the pilot has no other tasks, like flying and stabilising the aircraft; also, some combat scenarios are so rapidly changing, e.g. engagement of several air-to-air targets in supersonic cruise while maximising

Cockpit Design – Past, Present and Future

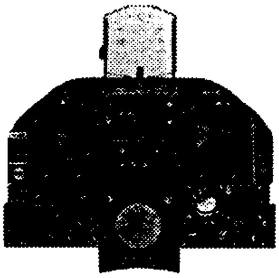


• Past

Gunsight, Radar scope, EW scope, Instruments and Armament panel

– ***Benefits*** Easy to learn, Easy to use, conventional

– ***Weaknesses*** Inflexible, single point failures, no growth potential, difficult to develop any situational awareness (SA)

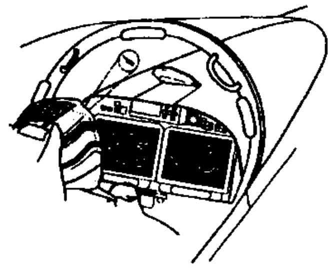


• Present

HUD, 3 or more Multi–Function Displays (5" or 6") and a Data Entry Panel (UFC)

– ***Benefits*** Flexibility, redundancy, and multi–mission capability

– ***Weaknesses*** Small displays, no HMD, poor global SA, workload intensive, effectively uses only 1/3 of panel for tactical display

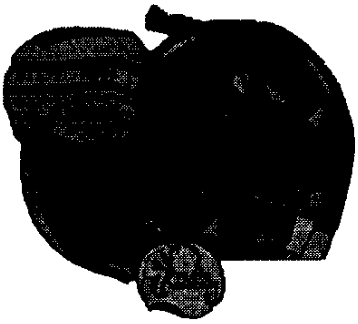


• Cockpit 2000

HMD, HUD, (2) 10" x 10" Multi–Function Displays, Automation, Decision Aids

– ***Benefits*** Increased flexibility, better global SA, reduced workload, off–boresight capability with HMD

– ***Weaknesses*** medium sized HMD and Displays, increasing mission requirements and off–board data requirements

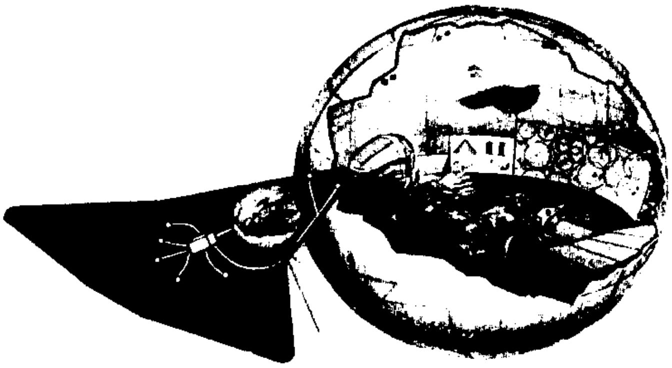


• Cockpit 2010

Larger, more capable, HMD, no HUD, 15" x 20" (300 in^2) Display, Windowing, Adaptive Decision Aiding, Extensive Automation

– ***Benefits*** Enormous flexibility, Very good SA, further managed workload, multi–mission–multi–target capability

– ***Weaknesses*** Exposure to laser threat



• Cockpit 2025

A 4' to 6' spheroid on which "the world" is projected, High Resolution HMD overlay and large Head–Down Displays, Adaptive Computer Intelligence and Internetted Data

– ***Benefits*** Very effective laser protection, very stealthy, immense situational awareness.

– ***Weaknesses*** No direct outside visibility

Figure 1 – From Flight Vehicle Integration Panel (FVP) Working Group WG-21 Advisory Report AR-349 on "Glass Cockpit Operational Effectiveness"

stealth, or approach to strike a well-depended target using ground cover, that the crew may be unable to take the most appropriate response in time. This situation points to three trends:

(i) automation of the flying-stabilisation and other 'routine' functions, so that the crew becomes a 'systems manager';

(ii) sensor fusion, to eliminate raw inputs, and present a coherent and cross-correlated 'picture' from several data sources (radar, IR, ESM, etc.) some of which may be outside the aircraft;

(iii) pilot 'associates', using artificial intelligence (AI) or other forms of situation assessment, prioritisation of actions and advice to the crew. All this entails a less direct control of the crew over the aircraft and systems, and increasing reliance on hardware and software to replace routine functions, freeing the on-board or remote crew for decisions requiring human judgement.

3.6. Aeromedical Aspects

The aeromedical aspects were already implicit in the consideration of cockpit and crew station design, since they relate to man-machine interaction (MMI) and affect human performance. There are also physiological problems, related not only to the demanding high-g air combat environment, but also to long-range and long-endurance flights, which can subject the human body to fatigue.

3.6.1. Human Performance Aspects

The glass cockpit, or the remote cockpit, is virtually indistinguishable from a simulator screen, with real time data. Thus the glass or remote cockpit could be used, with no hardware modifications, to fly operational missions, to simulate new missions, to review earlier missions, or to train crews. The benefits of this combined cockpit and simulation technology depend not only on the hardware and software used, but also on the understanding of human factors involved. The scope for progress and research in the latter is no less than in the former.

3.6.2. Laser Eye Protection

The glass cockpit would provide, as a by-product, laser eye protection. The remote cockpit would provide much more complete protection against almost every battle field threat, since the crew is not in the operational vehicle. Having the remote pilot in a well-protected area outside the battlefield, the best chance for an enemy would be to disrupt the data link or destroy the RPV unmanned vehicle. Laser eye protection can be provided by simpler means than a glass cockpit, and thus is not a primary justification for the latter. Low-power lasers pose a threat, even with rudimentary aiming, like with a rifle stock, in the case of take-off or landing, when a laser sniper lies near the runway. This risk is less for a high-speed low flying aircraft, and non-existent at higher altitudes. The use of high-power lasers as a ground-to-air or air-to-air weapon is a completely different issue in terms of technology, cost and complexity. The US Airborne Laser (ABL) program shows that it takes a Boeing 747 airframe to house a high-power laser able to knock-out Tactical Ballistic Missile (TBM) warheads at a distance of a few hundred kilometres.

3.6.3. Physiological Aspects of High Agility

Although the current generation of highly-manoeuvrable aircraft (F-15/16/18, Su-27, Mig-29, Mirage 2000) and their successors (F-22, JAST, EFA, Rafale, Gripen) take pilots close to the limits of resistance to g loads, it may be possible to go somewhat beyond the standard figure of 7-9g. It is expected that, with a warning at least 10 seconds in advance, an aircraft can outmanoeuvre a missile with 3 times the g-tolerance, e.g. a 9g instantaneous turn-rate allows an aircraft to evade a missile with a 27g-turn performance. It may be possible, through the development of special pressure suits, to raise the pilot g-endurance to 12-14g, at least temporarily, for evasive manoeuvres. This could counter missiles with 35-40g capability, but thrust-vectoring can achieve even more. Thus three levels of g-capability can be discerned:

- the manned aircraft, limited by the pilot at present to 7-9g, or perhaps 12-14g in future;
- the unmanned aircraft, limited at high-g by the increase in structural weight, perhaps to 20g;
- the missile, limited by thrust-vector control (TVC) performance, but able to pull much higher g's.

It should be borne in mind that a g-race could be won by the missile; the UTA is more complex, and would be more penalised by having all systems (e.g. fuel, avionics) and connections designed to resist high-g'. The manned aircraft, being limited by pilot g-endurance, would have to rely on passive or active self-defence other than evasion.

The introduction of vectoring nozzles in aircraft subjects the pilots to smaller g loads, but not in the normal direction, e.g. lateral for which the tolerance of the human body is less and long-term effects are less documented.

3.6.4. Fatigue in Long-Range Operations

Besides human factors in man-machine interaction, and physiological aspects of high agility, another major area of aeromedical research concerns fatigue in long-range flights or long-endurance operations. This aspect was less important in the Cold War period, with its obsessive concentration in the European theatre of operations, where the density and intensity of threats was paramount, not distance or dispersion. The change to out-of-area operations has shown that repeated in-flight refuelling can extend range and endurance beyond the fatigue limits of the crew. Also, even if the combat aircraft can be deployed in a few hours to the crisis area, its crew will need some hours of rest to be combat ready and fly the first operational mission. The alternative would be to use two crews: one to ferry the combat aircraft, and another 'resting' in a transport aircraft to arrive fresh at the crisis area.

3.6.5. Effects of Long-Endurance Flights

During a crisis there will be times when crews may have to fly extended periods of time, for predictable or unpredictable reasons, such as:

- deployment to a remote area, using in-flight refuelling, since no intermediate airfields can be used (for political or tactical reasons);
- extended combat air patrol, due to the need to control airspace with a smaller number of aircraft than optimum;
- additional strike mission, due to an urgent and unpredicted operational need, like taking an opportunity to hit a high value, elusive target.

It is well known that fatigue reduces human ability, and after a period of sleep, recovery of all senses takes some time. These effects need to be better studied and quantified, to assess the risk to which an aircrew is put, by extending missions into the 'reserves' of the human body.

3.6.6. Some Perennial Issues

There are traditional medical issues, such as hospital care or speedy evacuation, which remain as relevant as in the past, and for which modern technology and advance planning can bring better solutions. Even if, for some missions, the remote cockpit is the best solution, some aeromedical issues remain relevant, such as human factors in training, simulation and operations, and fatigue effects in long work shifts.

4. SYSTEMS INTEGRATION

The traditional discipline of design integration of an aerospace vehicle has gained in importance as the integration between flight dynamics, aerodynamics, propulsion, structures and materials becomes stronger, e.g. in the design of high-authority control systems with flight stabilisation, gust alleviation, thrust-vectoring and smart structural modes. A parallel activity concerns systems integration, between the avionics on-board the aircraft, the weapons it carries, the other systems in the aircraft, the sensor data on enemies and data exchange with friendlies. The design integration of the aerospace vehicle and mission systems are two interwoven tasks, even more so in the case of stealth designs.

4.1. Mission System

The term mission system is taken to encompass all the avionics on-board the aircraft, including sensors and data processing, hardware and software. They may conveniently be classified into radio frequency and electro-optical sensors, flight stabilisation, navigation, fire control, identification, communication, defensive and offensive systems, and computing.

4.1.1. Acquisition and Updating Costs

For an aircraft of the VIIth generation (e.g. F-22), avionics including flight control account for about 30% of the fly-away cost, compared with 25% for propulsion and 45% for the airframe. The cost of mission systems has risen from less than 10% in a WWII fighter, in successive post-war generations, and exceeded 50% of fly-away cost in some cases (e.g. F-111) in the Vth generation. In spite of major progress in capability, the relative cost of mission systems has improved, and reliability has made major gains. Nevertheless, mission systems still account for a large fraction of the cost of a combat aircraft; in addition, some of them are replaced within a decade, whereas the aerospace vehicle itself can be operated for several decades. It follows that mission systems are one of the largest components of the acquisition cost of an aircraft; they can also take a significant share of maintenance and support costs. In view of all this, it is perhaps paradoxical that mission system costs are those less well controlled in many aircraft programmes. The reason may lie in the wide variety of mission systems, and the tendency to specify more desirable features in each item. A global approach to the mission system is needed, not only to maximise synergies between different equipments, but also to avoid costly over-specification in some areas, and give better control acquisition, upgrade and maintenance costs.

4.1.2. Multi-Mode Phased-Array Radar

Radar is the primary all-weather sensor in a combat aircraft, and has often been a design driver, e.g. the diameter of the radar dish (or beam width or range) determines the size of the nose in an F-4, F-15 or Su-27, or conversely, nose size limits radar performance in an F-16, Mirage III/V or Mig-21. The replacement of mechanically-scanned dishes with phased arrays has allowed the simultaneous tracking of several targets, and the coexistence or interleaving of several modes: air-to-air, air-to-ground, terrain avoidance, etc. The use of conformal arrays should make radar performance less dependent on the size of the nose of the aircraft; the latter is a driver for the size of the whole airframe and thus aircraft overall cost. The multiplication of radar modes (more than 20 in some modern fighters) and the increasing complexity of ECM (electronic countermeasures) and ECCM (electronic counter-countermeasures) point to increased automation of radar operation, not just signal processing. Being an active sensor, radar gives away its position at long ranges; in this respect, the low-probability of intercept (LPI) radar, which attempts to disguise its pulses into the background electromagnetic noise, is an interesting development. A major enhancement in radar capability is provided by the synthetic aperture radar (SAR) mode, which uses aircraft motion to simulate a much larger antenna, thereby giving much higher resolution, close to mapping quality. Synthetic aperture is of as high value for attack aircraft, in target identification, as pulse Doppler with ground clutter elimination, is essential to intercept low flying aircraft.

4.1.3. Passive and Electro-Optical Sensors

Radar has the advantage of being an all-weather sensor, but gives away its presence at long range, to a radar receiver, which acts as a passive sensor. The most useful passive sensors are those which depend on natural radiation, rather than man-made emissions like radar. Electro-optical sensors, in the visible and infra-red portions of the spectrum, have their range limited by atmospheric absorption, except in certain windows, e.g. 1.5-2μ, 4-5μ and 10-12μ (μ = micron) wavelength bands for infra-red radiation, corresponding respectively to hot afterburner exhaust (around 1200 to 1500 C), hot engine sections (300 to 500 C) and ambient temperatures (around 15 C). Even in these atmospheric transmission windows, water vapour and dust cause absorption, so that electro-optical sensors operate well at night, but not in bad weather. They are much more difficult to detect than radar:

- radar, like any active sensor, is an emitter, or bright point, tracked easily by a receiver;
- infra-red or television, like any passive sensor, is a dark spot which can be identified only by mapping the brighter area around it.

Although electro-optical sensors tend to have a shorter range than radar, an Infra-red Search and Track system (IRST) is a very useful complement to radar, and invaluable as a stand-alone system, when passive observation and tracking is the preferred option.

4.1.4. Flight Stabilisation Systems

Flight stabilisation systems (already discussed in 2.3) are essential to give acceptable flying qualities to efficient aircraft designs, which may be statically unstable. Being safety critical, they usually require four independent channels, to tolerate two failures, with possibility of identification and disengagement of the 'faulty' channel through vote comparison. By four 'independent' channels, we mean the use of distinct hardware and software in each channel, so that a single software error or component failure cannot affect more than one channel. Flight stabilisation systems tend to use fast processors, to avoid time delays greater than 0.1 seconds from control input by the pilot to control surface deflection. Software development for flight control systems is the pacing item in several modem high manoeuvrability fighters, and still an operational problem in some of them. Given the close interaction of control algorithms, pilot models and flight dynamics, it is not easy to be sure where the key is to this unsolved, important problem.

4.1.5. Combination of Navigation Systems

Among the navigation systems, GPS is a favourite, due to its high accuracy (10m in military mode) and world wide coverage (with some degradation in polar areas). The cost of a GPS receiver (few hundred dollars) looks ridiculous compared with the cost of integrating GPS data with other on-board navigation system (usually hundreds of thousands of dollars). GPS can replace with advantage the traditional hyperbolic navigation systems (TACAN, LORAN, OMEGA), which have less accuracy, and smaller coverage (with the exception of OMEGA, which has world wide coverage, but is being de-activated). Since GPS is jammable, it should not be used as sole means of navigation, but rather as a complement or update to other systems, like TERCOM and inertial navigation system (INS). The combination of these three systems is highly effective, because:

- GPS is passive, and has high position accuracy, independent of time and location, but is jammable;
- INS is self-contained and non-jammable, but accumulates errors over time;
- TERCOM uses local emissions (e.g. radio or radar altimeters) to compare with a stored digital map, and thus is hard to jam and is quite accurate when over a good map grid.

Other means of navigation, like Doppler radar or star tracking, can be used as a complement, but the former is active and the latter cloud-cover dependent.

4.1.6. Fire Control Systems

A fire control system uses sensor data to identify and track a target, and commands the systems or advises the pilot on how to fly the aircraft to strike the target with the appropriate weapon. The key link, in the middle of the chain, is the identification and tracking of the target. This is a task traditionally entrusted to the intelligence and flexibility of the human mind, and which would be better passed to automatic target recognition (ATR) algorithms. This is easier to do for air-to-air targets, which can be analysed by a threat assessment algorithm, suggesting engagement priorities to the pilot. ATR also applies to ground targets, with some cueing help from automated scene scanning; the tracking function is easy to automate, if target contrast is sufficient.

4.1.7. Identification and Sensor Fusion

The old issue of identification has already been mentioned in passing; it has vexed military planners in combat or just patrol missions up to the present day. More must be done to prevent friendly fire and fratricide. The ambiguities of a single identification system are known: it confuses friend with an enemy which has learned the code; it also confuses the enemy with a friend with a malfunctioning system. Fusing data from several sensors on-board and exchanging data with AWACS or J-STARS aircraft, are methods to eliminate errors by comparison of multiple inputs. Unfortunately it is easier to say than to do: among a multitude of sensor inputs, to identify which relate to the same target, is a task which has proven difficult to automate in general. One method is to use one sensor to detect a potential target, and then cue the others to confirm its existence and characteristics.

4.1.8. Communications and Data Exchange

One of the keys to identification is data exchange, using data links like JITDS (Joint Information Tactical Data System). These links serve the wider purpose of exchanging data between friendly platforms, giving all of them a better situational awareness of the battle scenario, and providing for an more effective and coordinated use of forces. Voice communication, by UHF, has lost importance, except over friendly skies, or at short range in a formation, due to lack of discretion and low data rate. The case for HF, as long-range link or back-up to UHF, may be considered, although signal quality is very dependent on propagation conditions.

4.1.9. Defensive Systems and Manoeuvring

The defensive systems are usually passive, such as electronic counter measures (ECM) to jam hostile radars, or electronic support measures (ESM) to listen passively to emissions, or radar warning receivers (RWR) to detect incoming missiles and command the launch decoys; the latter may be flares against infra-red guided missiles or chaff against radar guided missiles. The multi-mode guidance systems of modern missiles are increasingly difficult to deceive, causing a need to use towed decoys, which combine radar and infra-red signatures, viz. operate in several bands of the EM spectrum. Evasive manoeuvres may not be effective against missiles with thrust-vector nozzles and able to pull more than 30g; thus the case arises for active self-defence systems (see 6.3.4).

4.1.10. Offensive Systems and Defence Suppression

The offensive systems locate targets and direct weapons at them. For a bomber, the defensive and offensive avionics alone are a major share of purchase cost, may take the longest time to develop, and may dominate maintenance tasks and training. In a fighter there is a tighter limit on the space, cost and complexity allowed for defensive systems. The exception is electronic support aircraft (like the Panavia Tornado ECR, F-111 Electric Raven or EA-6 Prowler) and the SEAD (suppression of enemy air defences) aircraft (like the F-4G Wild Weasel); the SEAD mission is very high-risk, since it involves silencing or attacking radars with anti-radiation missiles. The increasing costs of aircraft development make the development of specialised ESM or SEAD aircraft less affordable, although they are essential to the performance of strike missions over heavily defended areas with acceptably low attrition losses.

4.1.11. Computing and Data Exchange

High data rate links and fast processors are the key to many of the preceding avionics functions. The trend towards centralised or distributed computing has oscillated during the years, viz. centralised in the Vth generation (e.g. Saab Viggen), distributed in the VIth (e.g. F-18), back to mostly centralised in the VIIth (e.g. F-22). In the past the aerospace application has been the driver for miniaturisation of computers, which later benefited society at large. The civil computer market is so large and dynamic today, that it should be possible to adapt commercial computers, rather than make specific developments, like the Hughes processors for the F-22. The hardening and ruggedising of commercial computers should not be too costly at the design stage; the distinct production methods and smaller runs will mean that military computers will cost more than civil processors of similar speed and capacity, but the difference should not be as great as at present. This would suggest parallel development of ruggedised, hardened versions of each new generation of commercial computer chip.

4.2. Weapons

Aircraft weapons are conveniently classed in two groups: air-to-air (short range or beyond visual range missiles, and airborne lasers) and air-to-ground ('iron' bombs, rockets and accurate or precision guided munitions, viz. glide bombs or missiles). The gun can be used both in air-to-air and air-to-ground engagements.

4.2.1. Air-to-Air Weapons

Air-to-air weapons may be guided or unguided, depending on the air-to-air application. The unguided weapons are the bullets from a high rate of fire gun system used in close-in combat. The guided air-to-air weapons have either infra-red (IR) or radio frequency (RF) guidance to their target, e.g. sensing in the 3-5 micron IR emissions is used for short and medium range aerial combat. Their advantage is that they are smaller and cheaper than the radar-guided RF missiles. The RF missiles are all in the high frequency X and Ku band and are used for the longer range BVR (beyond visual range) engagement. The IR missiles detonate on impact and the RF missiles detonate from a sensor fused miss distance.

4.2.2. Short-Range Air-to-Air Missiles (AAMs)

The current NATO short range IR missiles are the US AIM-9M Sidewinder and the French Magic 2. Both of these missiles have restricted off-boresight angle (OBA) launch capabilities of less than 20 degrees due to narrow (stationary) FOV seekers and limited manoeuvre capability. These missiles are badly outclassed by the Russian AA-11 Archer and the Israeli Python 4 which have OBA launch capability out to 90 degrees and are coupled to helmet-mounted sights. This gives the pilot with Archer or Python missiles a first shot advantage during hard manoeuvring close-in combat (less than 8 Km range). The ASRAAM (Advanced Short-Range Air-to-Air Missile) programme has been the slow-paced brother of AMRAAM, and now NATO missile companies are feverishly developing high OBA missiles, like the US AIM-9X, and helmet-mounted sights, to close the gap, but the earliest initial operational capability (IOC) is early next century. This off-boresight capability is important in order to match the weapon to the super manoeuvring (post stall) aircraft, but the main motivation is simply to close a gap of vulnerability which affects western fighters flying against others equipped, say, with the Archer AAM.

4.2.3. Beyond Visual Range (BVR) AAMs

The vulnerability of aircraft to agile short range AAMs has put more emphasis on intercepting enemy aircraft at longer ranges. The beyond visual range (BVR) missiles usually fly in a navigation mode (e.g. INS) to the vicinity of the target, with final homing by active radar, IR/EO seekers or dual mode seekers. Semi-active radar guidance, with the radar of the launch aircraft illuminating the target, is possible in principle, but undesirable in practice since it limits the freedom of manoeuvre of the launch aircraft. Fire-and-forget BVR AAMs are the preferred solution, as ranges extend from 50 to 100 Km for rocket powered missiles, to more than 100 Km with ramjet propulsion. In the area of ramjet powered BVR AAMs, the former Soviet Union appears to lead the West, as it does in short-range OBA AAMs, but its financial situation may prevent it from keeping this edge. The standard BVR AAM in the West is the Hughes AMRAAM, but the UK requirement for the FAMRAAM is likely to set the standard for a ramjet-powered missile, with longer range and greater terminal manoeuvrability, leading to a much larger no-escape envelope.

4.2.4. Airborne Laser Weapons

The US is developing an airborne laser (ABL) aircraft (Boeing 747-400) for theatre ballistic missile (TBM) defence. The motivation for the ABL is the lesson learned from Desert Storm where the Iraqi Scud missiles came close to holding US Allies hostage. The ABL operating at 45,000 feet would use a 3 MW chemical oxygen iodine laser (lasing at 1.315 micron) to shoot down TBMs at 500 Km range during their boost phase. The ABL is scheduled for IOC in 2004.

4.2.5. Dumb or 'Iron' Bombs and Dispensers

The air-to-surface weapons are classified as unguided (dumb), accurate guided or precision guided. The dumb weapons are the free fall bombs and submunition dispensers which rely on ballistic solutions, known wind conditions, pilot skill and luck to hit near the target. The Mk 82 (500 lb), Mk 83 (1000 lb), and Mk 84 (2000 lb) general purpose bomb family is typical of the unguided air-to-surface weapon. Their advantage is that they require minimum interface with the aircraft and they are cheap (less than $ 5K). Their low cost is an illusion, if delivering them means exposing a valuable aircraft and an invaluable crew. Thus the current large stocks of 'iron' bombs may be unusable, except to the extent that some of them are converted to 'smart' weapons.

4.2.6. Accurate Guided Weapons

The accurate guided air-to-surface weapons have miss distances of less than 50 feet. This accuracy is good enough for large buildings, area targets and ships. Their guidance system could be EO/IR/RF scene area correlation or GPS aided INS. The AGM-84 Harpoon is an example of a RF scene area correlation weapon used for anti-ship missions. The current JDAM (Joint Direct Attack Munition) programme is developing a GPS/INS guidance kit for the Mk series bomb family. The weapon accuracy will depend upon the fidelity of the target coordinates and GPS accuracy. The cost of the JDAM tail fin kit is reported to be $17K.

4.2.7. Precision Guided Munitions

The precision guided munitions (PGM) have miss distances on the order of 10 feet or less. Their guidance can be either MITL (man-in-the-loop) or autonomous. The MITL systems consist of the following schemes:

(i) Designation of the target with a laser and the weapon guides itself to the laser spot. The laser designation can be from the launch aircraft, another aircraft or a ground observer. The GBU family of laser guided bombs (LGB) is typical of this semi-active guidance scheme;

(ii) The pilot selects the aimpoint by locking onto a target feature (edge or contrast match) before weapon launch using the weapon EO/IR sensor. The weapon guides itself to the target feature. This scheme is used for short range direct attack munitions since the pilot must be able to see the target before launch. The AGM-65 Maverick is typical of this type of PGM;

(iii) Using a data link on the weapon, the pilot locks onto a target feature after launch, using the transmitted weapon EO/IR sensor imagery, and the weapon guides itself to the feature. The GBU-15 and Walleye free fall weapons, and the powered SLAM are examples of this longer range indirect attack weapon. The pilot does not see the target before launch and can adjust the target cursor at any time during the weapon's flight to the target to improve the accuracy;

(iv) Using a data link on the weapon the MITL can "fly" the weapon into the target.

The cost of the MITL PGMs depends upon the extent of the avionics and propulsion onboard the weapon. The free fall LGBs cost typically $20-50K, whereas the data link and powered weapons exceed $100K.

4.2.8. Increased Stand-off Ranges

The autonomous precision guided weapons rely on matching sensed target imagery with stored target information. Current sensors are EO (Electro-Optical) and FLIR (forward looking infra-red) with SAR (synthetic aperture radar) in development. Onboard algorithms would compare sensor frames with the stored target information to detect the target, classify it, and then recognise the specific target feature (such as a window) to achieve the precision guidance. The ATR (automatic target recognition) technology is evolving rapidly and is scheduled for application on the JSOW (Joint Stand-off Weapon) and JASSM (Joint Air-to-Surface Stand-off Munition).

Desert Storm demonstrated the immense value of PGMs versus traditional dumb bombs. Laser and EO guided weapons represented only 7 percent of the total munitions expended during the war, yet accounted for a majority of the kills. The trend for PGMs is increased stand-off range to lessen the risk to the delivery aircraft and crew. These weapons use GPS/INS for navigation to the target area and then MITL through a data link or ATR for the terminal precession. The data link feature also provides in-flight monitoring of the weapons status, the ability to retarget en route and BDA (bomb damage assessment) by transmitting target imagery just before impact. Stand-off weapons of this type are the operational French Apache and US SLAM, and the developing US JASSM and SLAM-ER and the UK CASOM.

4.2.9. Trends for the Future Weapons

The air-to-air weapons for 2020 are expected to be similar to today's IR and RF guided weapons but will feature OBA greater than 90 degrees, better reliability and be much less expensive. They may combine BVR with terminal OBA.

The ABL will be operational against the TBMs and even perhaps cruise missiles and bomber aircraft.

The air-to-surface weapons will be predominately precision stand-off, both MITL and autonomous, to allow more targets to be struck with fewer tactical aircraft. The reliance of GPS for navigation will be lessened by greatly increased processing power and world-wide digital terrain data to 3 metre accuracy for INS updating. The INS updating would be by matching the terrain data with IR and RF sensor imagery. The increased processing power will make the ATRs more robust so that they can recognise a target sandwiched in among many similar looking targets. The main improvement in air-to-surface weapons is that they will be more affordable.

4.2.10. The Role of the Airborne Gun

For air-to-air combat, a 20 mm calibre is sufficient, and allows a high rate-of-fire, e.g. 6000 rpm (rounds per minute) for the Vulcan M-61 6-barrel Gatling gun used in US fighters. French (DEFA on Mirage 2000, Rafale) and Russian (Su-27, Mig-19) fighters tend to use 30 mm guns, with a slower rate of fire around 1000 r.p.m., which is still sufficient for air-to-air combat, and is useful in the air-to-surface role against soft skinned targets. The Mauser 27 mm calibre replacing the British ADEN 30 mm gun, and used in the Tornado and Eurofighter, is a compromise. True armour-piercing capability, to destroy battle tanks, requires a massive 30 mm gun, like the GAU-8 6-barrel Gatling fitted to the A-10.

4.3. Stealth or Low-Observability Features

Before low signature features are designed into an aircraft the priorities shown need to be examined:

- Mission planning - avoid threat, select conditions;
- Mission profile - speed, altitude, terrain following/terrain avoidance;
- On-board/off-board equipment - ECM, flares, chaff;
- Defeat endgame – manoeuvre;
- Low signature.

It should not be assumed a priori that low signature is the answer because any low-observability (LO) feature (like any non-safety of flight feature) is a life time penalty. The designer should not try to defeat the threat with signature alone, but rather should blend signature with mission planning and countermeasures to obtain a robust survivability strategy.

This paper will address radio frequency (RF) radar cross-section (RCS) from VHF (170 Mhz) to Ku (16 Ghz) bands, IR (infra-red) from mid-wave (3 microns) to long wave 12 (microns), visible and acoustic signatures. This choice of frequencies covers current threat systems.

4.3.1. Potential of Mission Planning

The first thing a designer needs to do, once the decision is made to go stealthy, is understand the threat. The major threat characteristic is the frequency of the radar since many RCS reduction features will be dependent upon the target size in wavelengths, D/λ where D is a characteristic dimension of the aircraft and λ is the radar wavelength. A handy expression for the wavelength in inches is $\lambda = 11.8/f$ where f is the frequency in Ghz. The polarisation of the radar is important since the characteristic dimension D is different for vertical and horizontal polarisations. Each threat radar system has a unique time line in terms of the time to acquire, track and fire a projectile. For example, if a threat surface-to-air-missile (SAM) has a time line of 30 seconds, it can be defeated by interrupting its radar coverage within the 30 seconds.

The resistance of the threat system to on-board/off-board jamming is important information to a designer as the survivability feature might be the integration of a piece of ECM avionics or a support jamming aircraft such as the EF-111, EA-6B and Tornado ECR. Usually, ECM equipment can be removed from an aircraft so that it is not a life time penalty when it's not needed. However, there may be a penalty to provide power and volume for the ECM equipment.

Deployment information is needed to do the mission planning discussed above. Terrain masking is a very effective way of denying the enemy early warning detection or interrupting a SAM system's time line and not paying a life time penalty. However, there are operational penalties with terrain following such as increased fuel consumption and pilot workload, and limited target viewing time.

After the possibilities of mission planning and profile, reduction becomes the next improvement, and radar signature is the most important. For operations in a variety of high threat scenarios, including cases where mission planning and ECM cannot cope with the threat, a stealth design has a major tactical benefit.

4.3.2. Tactical Advantages in Detection

For a given sensitivity and false alarm rate (FAR), the detectability of a target (or echo strength) is proportional to the radar cross-section (RCS) and inversely proportional to the fourth power of distance (because both the emitted and reflected signal are spherical waves, whose amplitude decays like the inverse square of distance). Thus the detection range R varies as the one-fourth power of RCS in m^2, where R_0 is the range for a target with 1 m^2 cross-section:

$$R = R_0\,(RCS)^{1/4}.$$

AIRCRAFT	RCS IN FRONTAL ASPECT	
	SOURCE (A)	SOURCE (B)
Boeing B-52H Stratofortress	10	100
Tupolev Tu-26 Blackjack	-	15
General Dynamics FB-111 Aardwark	-	7
McDonnell Douglas F-4 Phanton	-	6
Mikoyan-Gurevich Mig-21 Fishbed	-	4
Mikoyan-Gurevich Mig-29 Fulcram	-	3
Dassault Rafale - D	-	2
Rockwell B-1A Lancer	1	-
Rockwell B-1B Lancer	0.1	0.75
Northrop B-2 Spirit	0.01	0.1
Lockheed-Martin F-117-A NightHawk	0.001	0.025

TABLE II

Radar cross-sections (RCS) in frontal aspect from open literature

The RCS of aircraft is classified information, but there exists information in the open literature, e.g.

(A) "Stealth Warplanes", Bill Gunston, Osprey Publ., London, 1988.

(B) "Stealth", Doug Richardson, Salamander, London, 1991.

The variations in the data for the same aircraft in Table II according to these two sources, may say something about the reliability of these RCS values.

Although the RCS varies significantly with the look angle, e.g. it increases usually from head-on, to sideways or top-down, this is not the explanation for the discrepancy between the sources (A) and (B), since both claim to give a frontal RCS.

However both sources suggest that for the same class of aircraft, e.g. a bomber, the radar cross-section can be reduced by a factor of ten, equivalent to 10 dB, between:

(i) a conventional design (B-52H) and a blended wing body (B-1A);

(ii) a modest redesign (B-1A) to improve stealth (B-1B);

(iii) a totally new stealth design, starting with a clean sheet of paper (B-2) compared with an improvement of an existing design (B-1B).

Overall, careful attention to stealth at the design stage (B-2) can produce, relative to a conventional design (B-52H), a three-order of magnitude reduction of radar cross-section, corresponding to a 30-dB reduction in radar echo strength. If power rather than signal amplitude is used, these decibel values would be doubled. These values agree in order-of-magnitude with Figure 2, from Reference 1, which shows radar cross-section as a function of look angle.

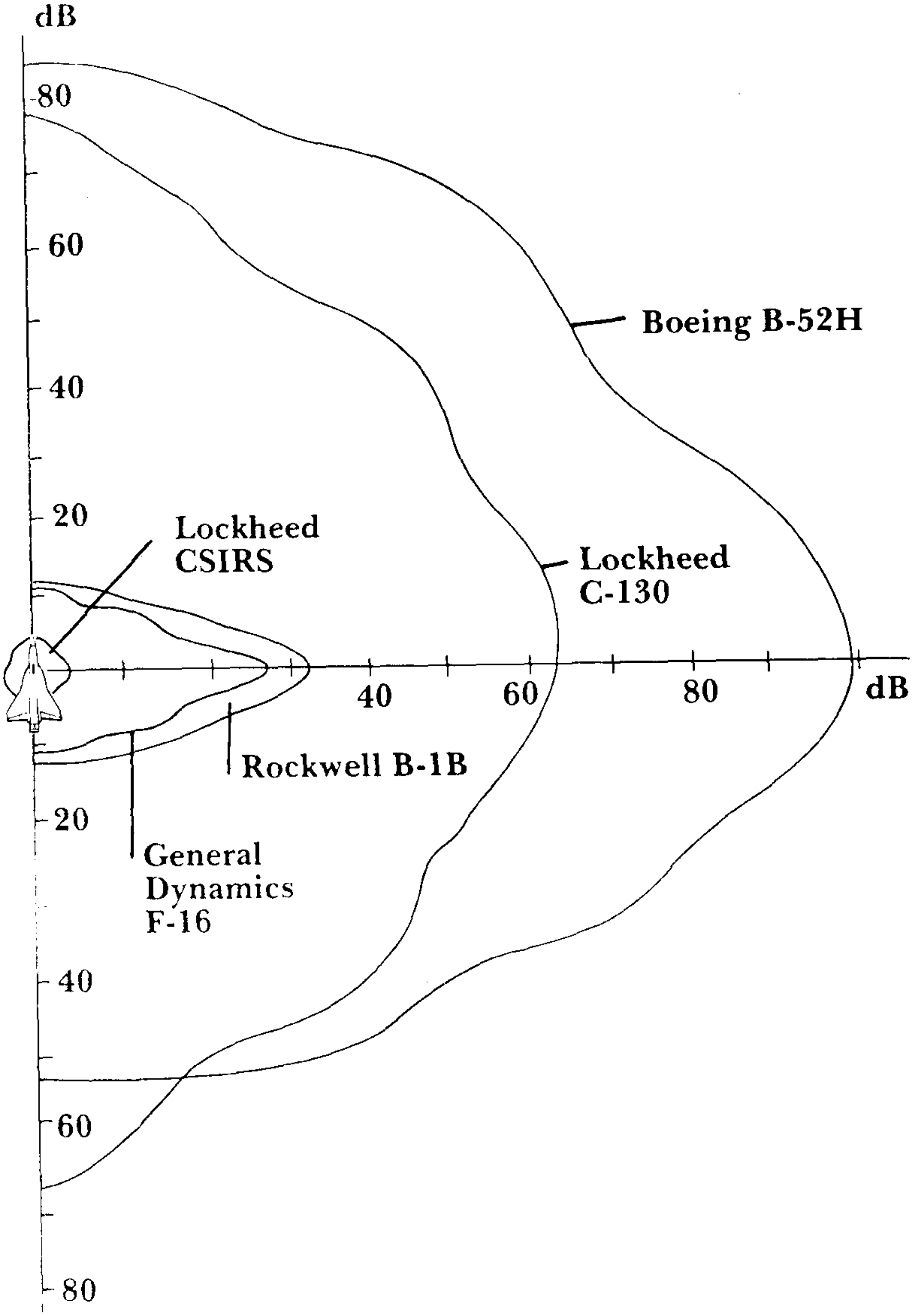


Figure 2 – Radar cross-section as a function of look angle

A common assumption is that the RCS of a manoeuvring fighter-sized target is 1 m^2, or 0.1 m^2 head-on, suggesting the following order-of-magnitude, tentative values:

(RCS in m^2)	DESIGN			
Type of Vehicle	Conventional	Blended	Improved	Stealthy
Bomber	10	1	0.1	0.01
Fighter	1	0.1	0.01	0.001
Missile	0.1	0.01	0.001	0.0001

TABLE III

Rough order of magnitude indication of head-on RCS of air vehicles

These data are applied to three examples: (i) a bomber penetrating a territory with air defences; (ii) a fighter in BVR air-to-air combat with AAMs; (iii) an aircraft striking at a site protected by radar-guided SAMs.

Concerning mission (i), for a long-range surveillance radar with a range of 300 Km against a 1m^2 target, a conventional B-52 type bomber (estimated RCS = 10 m^2) with box-shaped fuselage, corner reflectors at wing-fuselage junctions and engine pylons, exposed turbine faces, etc., would be detected at a range of 530 Km, and would have to rely on terrain masking. A blended wing-fuselage design, with some attention to detail, viz. an improved conventional design like the B-1B (estimated RCS = 0.1 m^2), would reduce detection range to 170 Km, allowing the bomber to pass undetected between radars more than 350 Km apart. A full stealth design, like the B-2 (estimated RCS = 0.01 m^2), would reduce detection range to less than 100 Km, and the aircraft could pass undetected at 100 Km from the radar, e.g. use a SRAM (Short-Range Attack Missile) with a range of a couple of hundred Km to suppress the radar before being detected.

Concerning mission (ii), for an air-to-air radar with a range of 100 Km against a 1 m^2 target, a blended fighter. The latter could fire a 50 Km range AAM, with a good chance of the target being destroyed, before the latter detected the stealth fighter. For example, if the two fighters were flying towards each other at 1500 Km/h, and the AAM had an average velocity of 3000 Km/h, the target would be destroyed at 38 Km range. If that shot failed, an immediate second shot would intercept at 29 Km, still beyond detection range of a stealth fighter.

Concerning mission (iii), a SAM fire control radar with a tracking range of 60 Km, would detect the blended fighter at 28 Km, stealth improvements would reduce it to 18 Km and stealthy design to 10 Km. If the latter fired an ARM at 15 Km range (like HARM), the radar would detect it at launch, unless it was a stealth ASM, which would be detected at only 3 Km range. For a Mach 4 missile, reaction time would be 3 seconds, and the missile would hit the target, with launch from a Mach 1 attack aircraft, when the latter was still at 12 Km range, still undetected.

The values assumed in Table III have no claim to accuracy or realism, and serve only as an illustration. They probably can be improved upon in a careful conventional design or a design for Very-Low Observability (VLO), so the benefits would be larger, even though these tentative estimates may already sound impressive.

4.3.3. Radar Scattering Cross-section (RCS)

The electromagnetic (EM) scattering sources are shown in Figure 2 and are the result of discontinuities. These discontinuities are physical geometry such as perimeter edges, corner reflectors or surface derivative (slope or radius of curvature), and current path discontinuities such as gaps, cracks, aperture edges and surface impedance changes. The fine grain inhomogeneities of the vehicle surface such as fastener heads and surface finish flaws can cause diffuse scattering and increase the RCS fuzz ball level.

Typical aircraft scattering sources are the result of the discontinuities discussed above. There would be specular returns off of the leading and trailing edges, the inlet and nozzle lips, and normal to the surface. Diffraction would occur at the nose and wing/tail tips. The travelling wave surface currents would be interrupted by the control surface gaps, access door cracks, and material changes such as going from the airframe to the canopy, IR window or radome. Discontinuities in surface slope or curvature (first and second derivatives) will cause RCS scattering and should be avoided by blending the wing, body and tail together.

The RCS reduction technique depends upon the primary scattering sources which depend upon the vehicle D/λ . The strategy for reducing the RCS is shown in Table IV.

RF Bands For Aircraft Size Targets	$D/\lambda < 3$ HF/VHF	$D/\lambda > 3$ Microwave
Primary Scattering Source	Diffraction Travelling Waves Resonances	Specular Reflection Apertures Surface Details
Scattering Reduction Technique	Radar Absorber Nulling Techniques	Shaping Radar Absorbers Shielding

TABLE IV

Techniques for reduction of radar cross-section

4.3.4. Techniques for RCS Reduction

Platform shaping for low signature is a matter of configuring the vehicle to minimise the number of specular return spikes and directing (or steering) then away from the sensor. The number of spikes can be minimised by having the platform consist of parallel lines. The vertical tails are canted to prevent a large side spike at low elevation angles. Notice that the orientation of the control surface and door gaps and cracks are such that their RCS returns are all in the same direction as the main spikes from the leading and trailing edge. In this way the spikes from these surface details are buried (or stacked) in the main spikes. The penalty associated with platform shaping and configuration blending will typically increase the aircraft take-off gross weight by 10-15 percent.

The RCS return from gap and cracks can be lessened by filling the surface discontinuities with a conductive filler or covering with a RAM (radar absorbing material) sheet so that there is electrical conductivity across the surface. Doors are a problem as they move as the aircraft flexes and it is difficult to maintain electrical conductivity. Doors need to be secured so that their movement is slight under flight loads.

If a cavity dimension is less than one-half the radar wavelength, the radar energy will not enter the cavity and will be reflected off the cavity entrance. This phenomenon is called aperture cut-off and explains why an AM radio (with wavelengths on the order of 1000 feet) doesn't work in a tunnel but a FM (wavelengths of 10 feet) does. As the radar frequency increases and the wavelength decreases, the RF energy will enter the cavity, bounce around, reflect off the end of the cavity (compressor face in an inlet and the turbine face in an exhaust duct), and eventually reflect back out of the cavity. The trick is to line the cavity duct with absorber and maximise the number of bounces so that the RF wave that exists in the cavity is considerably weakened. The number of bounces is increased by designing a cavity duct with line-of-sight (LOS) blockage to the end of the cavity. A typical duct shape for LOS blockage is an "S" or serpentine shape with an L/D (length over cavity diameter) of 2.5-3.5 for nozzles and 4-6 for inlets. The L/D values for the serpentine ducts represent a balance between short/light and acceptable flow performance (no separation). The engine can also be fitted with a front or rear frame which are engine mounted grids or turning vanes that limit the LOS to the compressor or turbine face. The front and rear frames can reduce the required inlet or exhaust duct lengths. But they add weight and pressure loss to the propulsion system. The inlet and nozzle lips need to be swept in line with the wing leading and trailing edges respectively and treated with absorber.

Shaping will steer the spikes of the specular reflections but radar absorbing material (RAM) will reduce the magnitude of the spikes. RAM is any material that will reduce the strength of the RF energy through its conversion into heat. A typical RAM material is carbonyl iron imbedded in a matrix of rubber or polyurethane. RAM can be either in sheet form (called MagRAM) coating the surface of the aircraft or imbedded in the structure (called radar absorbing structure or RAS). Aircraft edges (wing/tail leading and trailing edges or inlet/nozzle lips) usually incorporate RAS which typically is a carbon loaded honeycomb or structural foam. The depth of the edges should be about one third of the wavelength the design is trying to defeat. The edge RAS is typically very narrow band and does not work very well at off-design frequencies (wavelengths). A RAS design for 800 Mhz would have an edge depth about 6 inches since the wavelength is 15 inches. The edge absorber is tapered or stepped so that the resistance decreases from the tip to the back of the edge. An edge treatment weakens the reflected energy by tapering from a good conductor (where it is attached to the surface) to a poor conductor. The edge design would also have a thin resistive sheet on the surface to weaken the low frequency surface currents. The RAM for absorbing high frequencies is much thinner because the wavelength is much smaller. Here the thickness is approximately one-quarter wavelength to get both absorption and cancellation.

Figure 3 shows the typical low RCS design features. The RAM coating and RAS edges will add about 8 percent to the empty weight.

4.3.5. Infra-red Signature Reduction

IR signature reduction is very important and difficult. It is important because IR threats are cheaper than RF threats and they are proliferating to Third World countries. They are simple, user friendly and easy to maintain, and hence perfect for terrorist groups. In addition, IR detector technology is embryonic and growing fast. Besides IR threats are passive and difficult to detect (see 4.1.3), making warning more difficult. IR signature control depends on driving the contrast between the target and the background below the detection threshold of the threat, and the background is constantly changing. The only good news about IR threats is that they are relatively short range (compared to RF threats) and the atmosphere (clouds, rain, dust, fog, etc.) readily absorbs the IR energy. In addition, IR threats systems need to be cued, usually by the Electronic Warfare (EW) / Ground Control Intercept (GCI) network. Thus the IR threat system can be reduced to a chance encounter by denying the enemy EW/GCI (VHF/UHF) detection. The IR sources for an aircraft are shown in Figure 4 and the signature calculation in Figure 5. The IR emissions radiate at all wavelengths but are predominant over a narrow band depending on their temperature. The aircraft hot parts (engine, plume, exhaust, etc.) radiate primarily at the 3-5 micron medium wave infra-red (MWIR), whereas the airframe (due to aerodynamic heating) radiates at 8-12 Long Wave Infra-Red (LWIR). All reflections are primarily LWIR. The threat sensors are primarily in the LWIR band and the missile seekers at MWIR.

The strategy for controlling the hot parts emissions is to shield, cool the source and reduce the emissivity ε. The lower surface deck/plating on the F-117 and the upper surface deck on the AGM-129 advanced Cruise Missile are examples of the use of shielding. Increasing the engine bypass ratio from 0.3 to 1.2 can reduce the exhaust IR contribution by an order of magnitude. Using fan air to cool the exhaust duct is also an effective way to decrease the exhaust system IR. The aircraft IR emissions are linearly dependent upon the surface emissivity, thus the surfaces need to have a low value for ε (typically 0.3). The airframe emissions are due primarily to aerodynamic heating which means slow flight speeds if possible.

The surface reflections will depend on the time of day, background (look-up, look-down or co-altitude) and the surface reflectivity. Note that surface reflectivity is $1-\varepsilon$ which means a high value of ε to minimise the surface reflections. Clearly the designer has a difficult choice for the IR coatings unless a variable/adaptive emissivity coating is available.

The IR contrast signature is not always positive (hot target and cold background). Looking down at a low flying target over a warm earth can give a negative contrast (cold target and warm background) in which case the designer would like to heat the aircraft upper surface. Current IR system sensors are so sensitive that it is extremely difficult to reduce the IR signature below the contrast threshold. Thus, the designer should plan to deny EW/GCI detection, avoid areas of IR system concentrations, and deploy IR countermeasures such as flares if attacked.

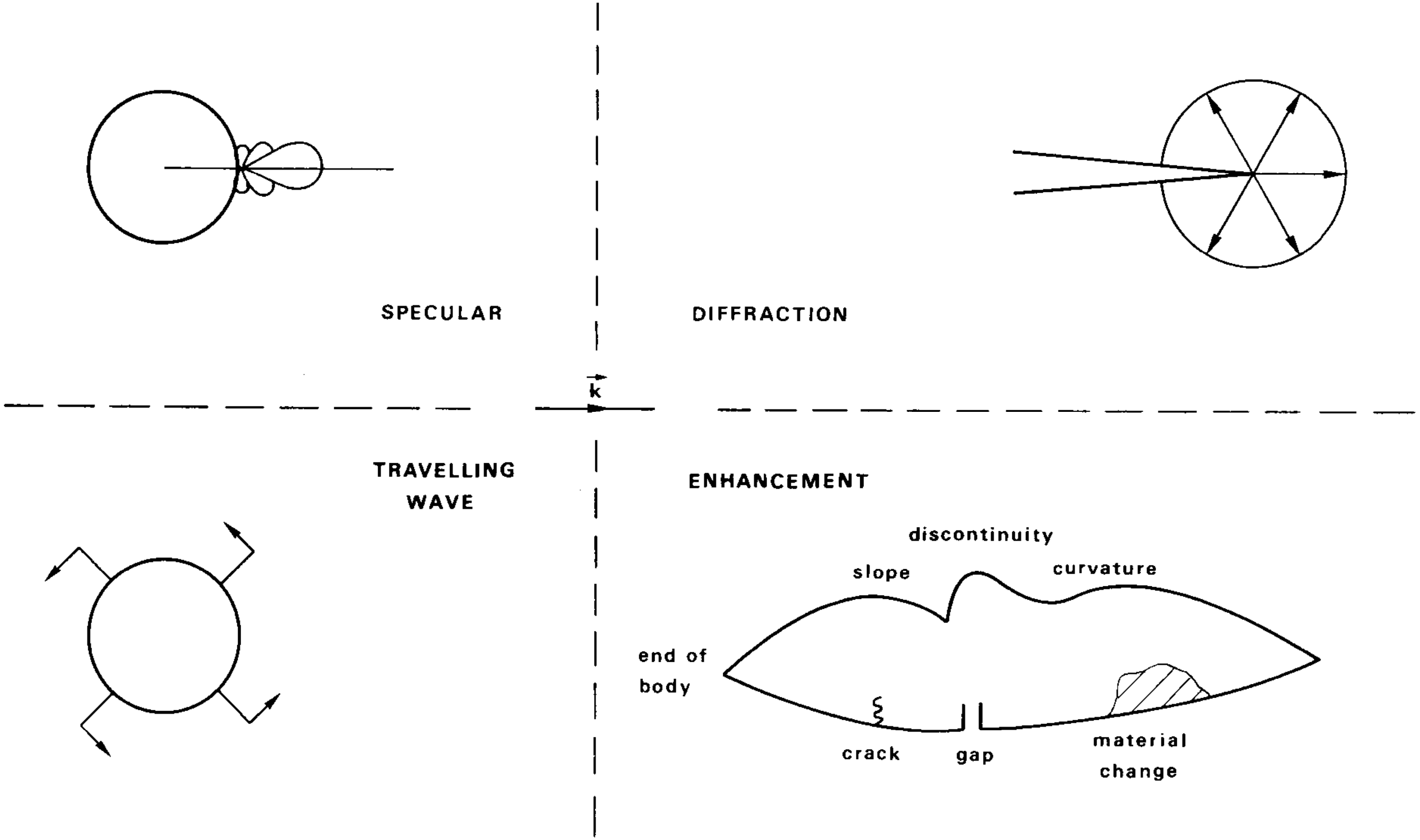
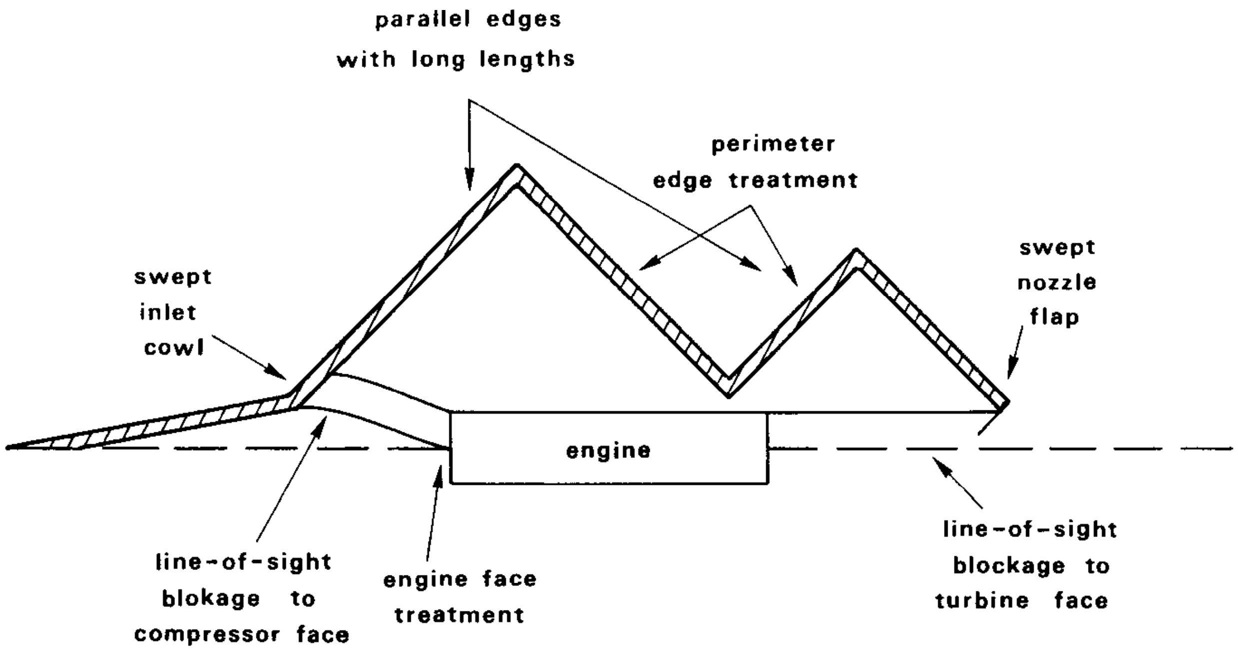


Figure 3 – Aircraft radio frequency scattering sources



sharp tips

all cracks, gaps, hinge lines treated and swept

spike stacking steering

inlet and nozzle dimensions < critical threat $\lambda/2$

side slopes < critical look-up/down angle

side shape: continuous second-order derivatives

Figure 4 – Typical design features for low radar cross-section

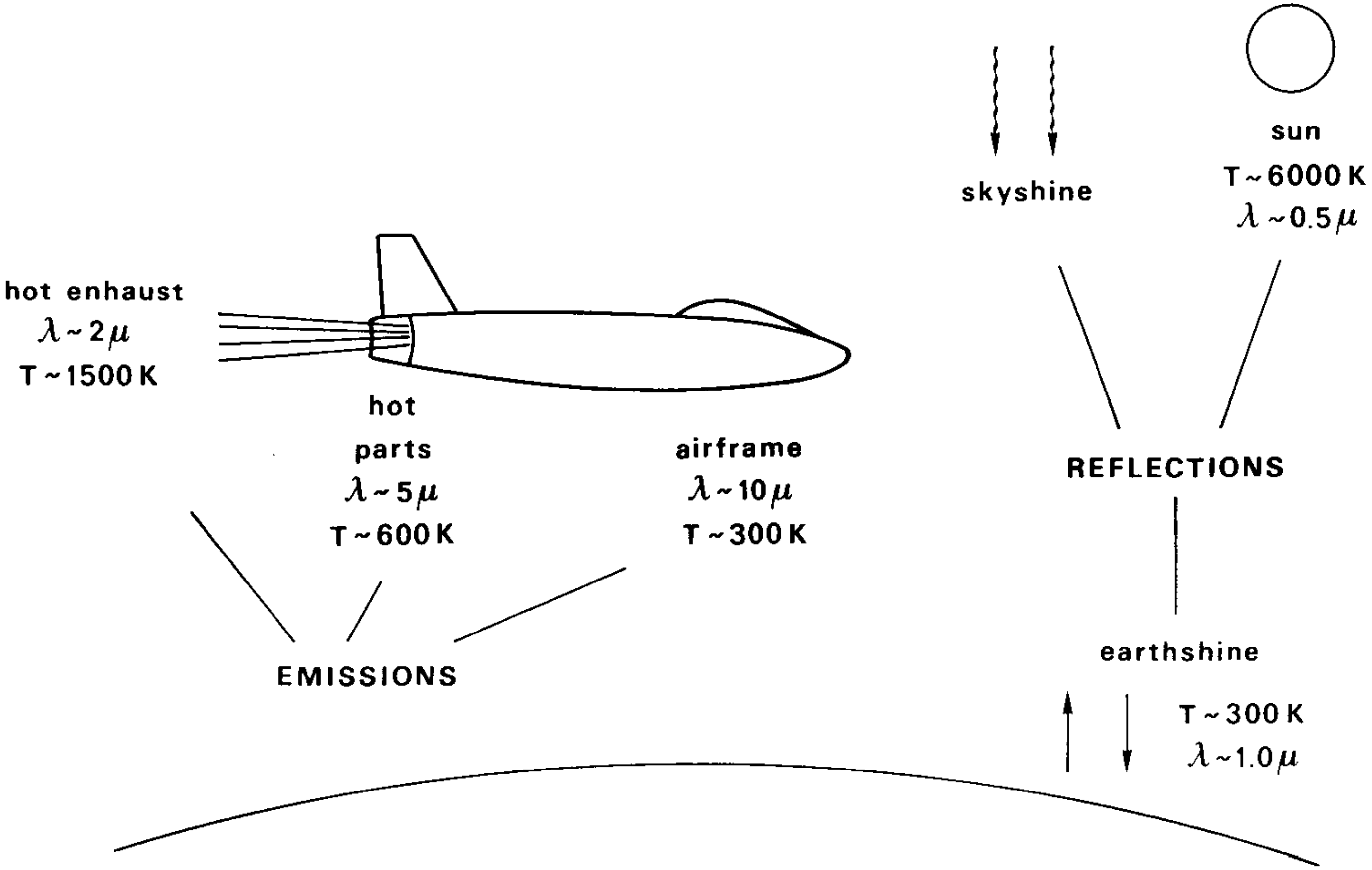


Figure 5 – Aircraft infra-red radiation sources and wavelengths

Table V - Factors affecting infra-red signature

*Total Coherent infra-red radiation

$I_{coht} = I_A + I_R = \text{Background}$

*Aircraft emissions: $I = \sigma \varepsilon f T^4 A_p$

σ - Stefan-Boltzman constant
ε - Emissivity of radiating surface
f - Distribution of energy in band of interest
T - Absolute temperature of emitter
A_p - Projected area

*Aircraft heat sources

$I_E = I_{\text{Hot parts}} + I_{\text{airframe}} + I_{\text{plume}}$

Representative temperatures:

Airframe - ISA Sea level	288 K
Mach 3, tropopause	996 K
Hot metal	1000 K
Plume - without afterburning	1500 K
Plume - with afterburning	2000 K

*Infra-red energy reflected from aircraft

$I_R = 1 - \varepsilon (E_{sun} F_{sun} + E_{earth} F_{earth} + E_{sky} F_{sky}) A_n$

*Infra-red (IR) sensor bands		wavelength	absolute temperature
Fire Control:	short wave (SWIR)	1-3 μ	1000 - 3000 K
	medium wave (MWIR)	3 - 5 μ	600 - 1000 K
Infra-red search and track			
	long wave (LWIR)	8 - 12 μ	250 - 370 K

4.3.6. Visual Signature and Identification

Some threat systems, such as hand held IR missiles and small arms gunfire, are cued by visual detection. The visual signature is similar to IR in that it is a contrast signature. This means that sometimes the designer wants a high reflectance surface (looking up at a target with a bright sky background) and other times a low reflectance (looking down a target with a terrain background). This is why traditional camouflage patterns for aircraft are sky blue or grey below, and ground-like paint schemes (olive, brown, sand) above. The operator should select the conditions, such as flying at night, shielding with terrain and flying below 30,000 feet to prevent contrails, in order to minimise the visual signature. Camouflage is one of the oldest forms of reducing visual signature. Low Light Level Television (LLLTV) and image intensifiers are modern ways of enhancing it.

4.3.7. Noise of Airplanes and Helicopters

The major consideration for reducing the acoustic signature is the careful selection of the operating conditions such as avoiding populated areas (the human ear is the number one acoustic sensor), low power levels and low speed (no sonic booms). If the target is in a populated area, then try to pick a noisy background so that the acoustic signature is masked by the background. The reduction of noise signature of an aircraft is not straightforward, and may in fact be more difficult than minimising radar cross-sections. For an attack aircraft in high-speed low altitude flight, there is no universal agreement as to whether engine or aerodynamic noise, are dominant. Helicopters have a characteristic noise, which can be heard miles away, and is due to blade-vortex-interaction (BVI), i.e. each blade cutting through the wake of the preceding.

4.3.8. Combination of Low Observability Features

The design of low observable features into an aircraft should be undertaken as a last resort. Once it has been determined that mission planning to avoid the threats or using speed, altitude, on-board/off-board equipment, and manoeuvre to defeat the threat will not work, then reducing the signature of the aircraft should be examined. Stealth features, just like any non safety-of-flight or performance feature, will carry a lifetime performance penalty. Once the decision is made to design the aircraft for reduced signature, the design guidelines discussed earlier in the paper should be followed. All signatures should be addressed so that the signatures are balanced (i.e. one signature is not lower than it needs to be relative to the other signatures). It takes only one signature to detect an aircraft, e.g. a contrail alerting and reducing system has been developed for the B-2.

4.4. Stores Carriage

Stores, either air-to-air or air-to-surface missiles, unguided rockets, guns, dumb, smart or precision guided bombs, dispensers, and fuel tanks, and guidance and navigation system pods, electronic warfare pods, or decoy launchers can be carried internally or externally. The former takes-up valuable internal space, and drives-up aircraft size and cost, whereas the latter degrades performance and stealth features. The compromises on store carriage are made easier by miniaturisation of stores and conformal or semi-recessed carriage.

4.4.1. Internal Guns or Gun Pods

The internal gun is still a basic fit, as last ditch air-to-air weapon, and low cost ground attack weapon against soft targets. An internal gun takes-up valuable volume and adds weight, and may require cooling, and a decision has to be made whether to store spent cartridges or how to eject them safely. Integration of a gun system is not a trivial task, as vibration may affect avionics, and gas ingestion can stall the engine. Some aircraft (like the McDonnell F-4C/D Phantom II of the US Navy) started without a gun armament, and had an internal gun fitted at the expense of a smaller radar dish (the Vulcan M-61 20mm gun in the F-4E of the US Air Force). If the external gun is to be carried as standard, this is not a good solution, because it takes up one pylon and the increased drag will degrade high-speed performance.

4.4.2. Carriage of Air-to-Air Missiles

The carriage of short range air-to-air missiles at the wing tips for self-defence is standard on several fighters since the IVth generation (e.g. F-5, F-104, Mig-21). Larger aircraft carry up to 4 beyond-visual-range air-to-air missiles semi-recessed (e.g. 4 AIM-7 Sparrow in the F-4 and F-15). The complement of air-to-air missiles in fighter aircraft has tended to increase, from a single Matra R.511 in the Mirage III, to 10 short and medium range AAMs in a Su-27.

4.4.3. External or Semi-Recessed Carriage

External carriage, even of small air-to-air missiles, may substantially degrade supersonic performance, due to the increase in drag. In this respect, semi-recessed carriage is much better, when feasible. A good example of the staggered semi-recessed carriage is radar-guided BVR AAMs in the Tornado ADV (Air Defence Variant), carefully designed to avoid interference with the landing gear while taking advantage of the longer fuselage relative to the IDS (Interdiction Strike) version. Another good example is the carriage of AIM-7 Sparrow missiles semi-recessed under the fuselage of the F-15, with additional AAMs at the corners of conformal fuel packs.

4.4.4. The Internal Weapons Bay

Internal carriage of air-to-air missiles was a feature of the Convair F-102 Delta Dagger and F-106 Delta Dart, aimed at preserving supersonic performance. Earlier aircraft, like the Northrop F-89 Scorpion and Avro CF-100 featured internal, wing tip pod, or leading-edge carriage, of AAMs or unguided rockets. The F-22 features missile bays again, not just for aerodynamic performance, but also to avoid degrading stealth characteristics.

4.4.5. Carriage of Bombs and PGMs

The F-117 Nighthawk also has a weapons bay, for stealthy carriage of two 2000 lb bombs, which appears to be the achievable standard in a modern design; the JSF designs chosen for development can carry internally two PGM plus, in Boeing's case, two AAMs. A substantial warload will require external carriage, in effect negating the low radar cross-section (RCS) of a stealthy design. The issue of weapon bay capacity applies equally to dumb or smart bombs or precision-guided munitions.

4.4.6. Miniaturisation of Bomb Warheads

The trends towards smart bombs and PGMs begs the question: are large warheads, carrying hundreds of pounds of explosives still needed, as in the time of dumb bombs? By using smaller warheads, and folding aerodynamic fins, a larger number of PGMs can fit into an internal weapons bay. Given the large investment made into stealthy aircraft designs, it might be worthwhile to make also a fraction of that investment in weapons which do not degrade stealthy features.

4.4.7. Stand-off Air-to-Surface Weapon

A long-range air-to-surface missile, like the IAI Popeye, McDonnell Douglas Slam, or Matra Apache, is too large for internal carriage. Since these weapons are released at considerable stand-off distances from their targets, the case for stealthy carriage is not as compelling. On the other hand, using stealthy features on the air-to-surface missile design can be quite effective in reducing an already small RCS, to the extent of making defence against this weapon rather difficult. The combination of stealthy aircraft and missile is most effective, since missile launch can be undetected, and its presence known when little warning time is left. Internal carriage is an added bonus, since it does not degrade the stealthiness of the launch aircraft. The US JASSM is designed for internal carriage on the B-1, B-2 and F-117.

4.4.8. Navigation and Guidance Pods

External pods, e.g. for navigation, night flying, electronic countermeasures, release of decoys and defensive aids, are a convenient way of adding these capabilities as an afterthought, or to avoid a lifetime penalty, by fitting them only when necessary for a given mission. However, given the disadvantages in flight performance and stealthiness, it is wiser to plan on internal carriage from the start of the design process. This leads to the topic of design integration.

4.5. Design Integration

Integration is the key to a successful aircraft design. Without integration the design is a point design with limited mission flexibility, poor supportability and probably unaffordable. Right from the beginning the design must address mission growth, supportability and cost. These features must be as much a part of the configuration trade study as engine type, T/W (thrust-to-weight), W/S (wing loading), aspect ratio, wing sweep, structural materials, etc.

Mission growth examines the cost vs. payoff of various payloads, growth avionics, and different mission requirements. The instances of air-to-air fighters carrying out air-to-ground missions are many. The design rule for fighter aircraft is to design for low W/S and high T/W so that the aircraft could carry out both air superiority and tactical strike if called upon.

4.5.1. Minimising Production Cost

Design for low cost means integrating those features into the configuration that will reduce the acquisition cost and improve supportability. To reduce the acquisition cost, the design must incorporate the features of a manufacturing friendly design. Manufacturing friendly means that manufacturing personnel are influencing the design daily from the very beginning. The design adheres to the following time-proven guidelines for reducing manufacturing (fabrication and assembly) hours:

- KISS (Keep It Small and Simple);
- Minimum part count;
- Minimum touch labour;
- Minimum holes drilled (major source of rejected parts);
- Right/left hand side (RHS/LHS) part interchangeability;
- Self locating features on all parts;
- Maximise room temperature processes;
- Minimise the number of different materials.

Keep It Simple is very important. Any complicated feature or new technology must "buy" its way onto the design. Both industry and government have been guilty in the past of integrating technology into a system solely for the sake of technology (making it more modern or state-of-the-art). This practice invariably increases the cost and risks.

4.5.2. Reducing Support Requirements

If supportability is not designed in from the beginning, the aircraft could end up being a "hangar queen". The designer must remember that the major portion of any aircraft's LCC (life-cycle cost) is operation and support. An aircraft with good supportability will be more available for missions, capable of high sortie rate during a surge, and more affordable overall during peacetime operations. Designing for supportability means packaging equipment one-deep with generous access panels. The system is designed around common support equipment that is readily available and minimises any peculiar support equipment. Maximum use of off-the-shelf equipment is basic design rule with any new equipment having to "buy" its way onto the vehicle. The RHS/LHS interchangeability is a good support feature also as it reduces the spares pipeline inventory.

4.5.3. Multi-Function Design Features

Integration also means designing the aircraft equipment and subcomponents to do more than one function. For example, thrust vectoring would let the propulsion system propel the aircraft and provide control forces for manoeuvre. The thrust vectoring could also reverse, giving the aircraft a short landing distance and the capability to move backwards on the ground. Brackets, hangers and clips should be designed to mount more than one piece of equipment if possible. This reduces part counts which lessens acquisition and support costs.

5. TYPES OF AIR VEHICLES

The main missions to be considered are air superiority and interception, and strike and interdiction, and an assessment needs to be made of the various options available: CTOL or STOVL airplanes, helicopters or rotorcraft, and unmanned air vehicles (autonomous or remotely piloted).

5.1. Air Superiority and Interception

The key issue is the sharing of capability between the aircraft as a weapons platform and the armament, namely air-to-air missiles and guns. Short-range air-to-air missiles with large off-boresight ability (OBA) can cause fratricide problems, whereas beyond visual range (BVR) air-to-air missiles lead to the mutual kill problem. The progress in both classes of AAMs poses an increasing challenge to aircraft survivability.

5.1.1. AAMs with Large OBA Capability

The fielding of the Soviet A-11 Archer (and also Israeli Python 4) missile, has left Western aircraft at a disadvantage, given that these missiles, coupled to a helmet-mounted sight, have a much wider engagement envelope than the AIM-9M Sidewinder and Matra Magic in NATO service. Clearly the West has taken too long to bring to fruition the ASRAAM (Advanced Short Range AAM), which should have been developed in parallel with AMRAAM (Advanced Medium Range AAM), now being fielded as the AIM-120. This failure of western intelligence will take some years to be recovered, and the lost standardisation on the ASRAAM may give way to a split with other contenders like AIM-9X designs.

5.1.2. The Expanding 'No-Escape Envelope'

Increasing the off-boresight capability of short-range AAMs from about 10-20° in the older generation to about 90° in the new generation, is one factor limiting the effectiveness of the escape manoeuvres an aircraft can perform. The other factor, is the limitation of the pilot to 7-9g instantaneous, and less sustained, allowing out-manoeuvring of an AAM with a 27g turn capability, but not an AAM with thrust vector control, which can pull more than 30g. The combination of these two factors is an expanded 'no escape' envelope for the target of a modern short-range AAM, with large OBA and high manoeuvrability.

5.1.3. The Self-Kill and Fratricide Problems

There has been at least one case of an aircraft being shot down by an air-to-air missile it fired earlier on in a manoeuvring engagement. There have been reports of a version of the Su-27 Flanker, with rearward facing radar, and an AAM able to turn over 180°, to hit an attacker in the tail position. Achieving a 180° turn is quite possible, using thrust vector control, just after launch, when the speed is low, and a small turn radius allows a quick turn (this has also been demonstrated in the West). Such developments increase the risk of hitting a wing man, or other forms of fratricide, unless an imaging sensor is developed which is able to distinguish enemy and friendly aircraft.

5.1.4. Beyond-Visual Range (BVR) AAMs

As the 'no-escape' envelope of short-range AAMs expands, the best chance of survival is to intercept enemy aircraft beyond visual range. The rocket-powered BVR missiles, such as the AIM-7 Sparrow, and its successor AIM-120 AMRAAM, have ranges of tens of kilometres, the exception being the larger AIM-54 Phoenix, arming the F-14, which has a range of over 100 Km. Rocket powered missiles, at long range, after burn-out, have to depend on residual kinetic energy, and cannot sustain hard manoeuvring against an evasive target. The adoption of ramjet propulsion, allows AMRAAM-sized missiles to have ranges of more than 100 Km, and being powered all the way, gives a better terminal manoeuvring capability, as in the UK FAMRAAM requirement.

5.1.5. The Mutual Kill Problem

The BVR AAM can lead to the mutual kill problem, which may be exemplified as follows:

- a blue aircraft detects red first, and fires a BVR AAM;
- before red is destroyed, it detects blue, and fires back a BVR AAM;
- blue is unable to escape, and is also destroyed.

The difficulty in overcoming the mutual kill is the need to detect red, fire the BVR AAM and destroy red, before it can detect blue and fire back. This is the rationale for stealth in air combat, to delay enemy detection and also for supersonic cruise, to allow speedy escape after missile launch.

5.1.6. Achieving High Exchange Ratios

It should be borne in mind, that in any forthcoming conflict, NATO forces will be expected to achieve success with very low casualties. Thus the risks of fratricide and mutual kill must be reduced. This may not apply to a rogue state, which could be quite happy at an exchange ratio close to unity, no matter how it was achieved.

5.1.7. Combination of Short-Range and BVR AAMs

The French have been unique in replacing the short-range Matra Magic and long-range Matra Super 530, by a single missile, the MICA, covering the full spectrum from dog-fight to BVR engagement. The obvious advantage is that it is no longer necessary to split the AAM complement into short-range and BVR types: all AAMs can be used in both roles. The development of the combined AAM has led to the requirement for MICA to be not much larger than Magic or Sidewinder, and yet approach the capability of AMRAAM. This compromise will become more demanding as short-range AAMs become more manoeuvrable and BVR AAMs have longer ranges. Also, MICA may be expensive as compared with a short-range only AAM. On the other hand, there is a trend to give high terminal manoeuvrability to BVR AAMs, which makes them suitable for short-range engagements, admittedly at high cost.

5.1.8. Is the Air-to-Air Gun needed?

The rationale for the air-to-air gun used to be as a last ditch defence in a dog fight, after the short-range AAM had failed, or when the complement of AAMs was exhausted. With the expanding 'no escape' envelopes of modern AAMs with large OBA, the chances of ever coming within gun range of an enemy are smaller. The larger AAM missile complements of modern fighters, allow more engagements before the AAMs are exhausted. In the event fuel outlasts the AAMs, a fighter would be better advised to leave the air combat scene, rather than try to survive on gun armament alone. Thus the dedicated air-to-air gun may have little more value than a false or dubious psychological assurance to the pilot in air combat; the space, weight and integration penalties of the gun may be better justified as a weapon against poorly defended targets (e.g. transport aircraft and helicopters not armed with AAMs), or as a cheap ground attack weapon. Even a helicopter with AAMs could be more than a match to a fighter left to the internal gun. The air-to-ground use of the airborne gun, could also be high risk, because radar-directed anti-aircraft guns have longer range, larger calibre and comparable or higher combined rate-of-fire. Besides, even shoulder-fired SAMs, which can be easily concealed by an infantry man, have longer range than the airborne gun. In conclusion, in order to be able to use its gun, the fighter has to come, for air combat, within the no escape envelope of modern AAMs, and for ground attack, within lethal range of radar-directed guns and all types of SAMs. Its use is thus restricted to intercepting unarmed aircraft, 'keeping the heads down' in a bomb pass, or attacking soft ground targets which are known to be unprotected by modern air defence systems (if it is possible to be sure of that?). In other cases, trying to use the airborne gun could do more harm to the pilot than to the enemy. Thus, if the gun is still fitted to a modern fighter, the pilot has to judge wisely when to try to use it.

5.2. Ground Attack and Interdiction

The increasing vulnerability of attack aircraft to air defences, has led to the use of fewer precision-guided munitions to destroy a target at longer stand-off distances. Four generations can be discerned: the 'iron' bomb, the glide bomb, the air-to-surface weapon, and the stand-off weapon. The penetration to the target area, to launch an air-to-surface weapon, even at stand-off ranges, may require the cooperation of ESM (Electronic Support Measures) and SEAD (Suppression of Enemy Air Defences) aircraft, as well as targeting and coordination by J-STARS and AWACS aircraft.

5.2.1. The 'Iron' Bomb, Multiple Attack Age

The times when targets could be attacked by dropping tons of bombs in multiple successive attacks, are gone. Even during the second World War, such tactics brought heavy attrition when attacking well defended targets. Given the high-value of modern aircraft, and the effectiveness of low cost anti-aircraft weapons, the casualties and attrition of such missions cannot be contemplated. The assurance that even a remote area is 'safe' for bombing no longer exists, as shoulder-fired surface-to-air missiles are so easy to conceal, and in widespread availability world-wide.

5.2.2. Radar-Guided Anti-Aircraft Guns

The Israeli experience during the Yom Kippur War proved the effectiveness of high-rate-of-fire radar-guided anti-aircraft guns, such as the quadruple ZSU-23 mount using 23 mm canon, with a combined rate-of-fire of 4000 rpm. The Vulcan M-61, with a maximum rate-of-fire of 6000 rpm should be equally effective out to a 2 Km range. Modern anti-aircraft tanks, like the Gepard, mounting twin 35 mm Oerlikon canon with a rate-of-fire in excess of 1000 rpm, should be effective to longer ranges of 3-4 Km. To survive these radar-guided high-rate-of-fire anti-aircraft gun systems, the attack aircraft needs at least to replace free fall weapons with glide bombs, released more than 4 Km from the target.

5.2.3. Shoulder-Fired Surface-to-Air Missiles

The shoulder-fired surface-to-air missile has improved markedly in the last two decades:

- cooled IR detectors allow aircraft to be attacked from all aspects, not just from behind;
- dual-band IR seekers, operating in the 2μ, 5μ and/or 10 μ band, are more difficult to decoy;
- the range and altitude envelope is expanding out to 10 Km and 4 Km respectively.

The production of these weapons by less scrupulous states like China, and their proliferation to violent factions around the world, means that this threat may exist anywhere, even in remote third world areas. To survive shoulder-fired surface-to-air missiles, the attacker must use air-to-surface missiles with a range of at least around 10 Km. To achieve such ranges of tens of Km, glide bombs need to be released at higher altitudes, facilitating detection of the attacking aircraft.

5.2.4. Mobile and Fixed Surface-to-Air Missiles

The first generations of surface-to-air missiles (Soviet SAM-2 Guideline, SA-5 Ganef, American Nike Ajax and Hercules, British Bloodhound and Thunderbird) tended to be too large for use at anything other than fixed or prepared sites, and were limited in low-altitude coverage; ranges varied from tens of kilometres to a couple of hundred, the latter case mostly with ramjet propulsion. The SAM-6, with its integrated rocket-ramjet propulsion, was compact enough to be carried in considerable numbers on mobile launchers; the continuous-wave (CW) radar illumination allows low-altitude engagements against ground clutter, as pioneered in the West with the Hawk. The new generation of surface-to-air missile systems, like the US Patriot and Russian SA-10 and SA-12, are designed to cope with small or high-speed targets, like cruise missiles and, to some extent, re-entry vehicles (RVs) of tactical ballistic missiles (TBMs). They become formidable weapons when used against strike aircraft, whose radar cross-section is much greater than that of cruise missiles (CMs), and whose speeds are closer to CMs than to RVs. The long range and high lethality of these advanced SAM systems is pushing towards the use of air-to-surface missiles with ranges of hundreds of kilometres, like the French Matra Apache, British Casom, US JASSM or Israeli Popeye. As an example of available performance, JASSM has 200-300 mile range, weighs 2200 lb (close to Mk.84 bomb) and cost less than half-a-million dollars.

5.2.5. Cost of Destroying a Target

It has long been argued that it is not cost-effective to risk a high-value strike aircraft, dropping a cheap 'iron' bomb, with low probability of destroying a target, in a pass over a well defended area. The argument has led from dumb to smart and then to precision guided monitions (PGMs), and also to increasing stand-off ranges from a few Km, to tens and now hundreds of Km. This evolution in precision guidance and stand-off range has been accompanied by an increase in weapon cost, to the extent where the weapon may be more expensive than the target it is used to attack; yet military need may drive such application, e.g. using a cruise missile worth more than a million dollars to destroy an ammunition depot which may not contain that much worth of ordnance. Concerning battle tanks, their value may justify using a sophisticated attack missile, but that may not be case for an armoured personnel carrier, or a truck or jeep. Such soft targets should be attacked by munition dispensers carrying terminally guided sub-munitions. The latter can also be effective against the thinner top armour of tanks. Similarly, airfield attack by flying over with a munitions dispenser is too high a risk, and this mission must be passed to CMs or UAVs, or a munitions dispenser launched at stand-off distances. A more difficult case is to strike at well dispersed, low-value targets, like jeeps and trucks, which are probably best left to ground forces. Thus air strikes with precision-guided stand-off weapons and sub-munition dispensers are cost-effective against high-value well-defended targets or troop and armoured vehicle concentrations, viz. to break the backbone of an offensive, and disrupt command, control and logistic systems. The cost of a CM is about US$ 1 million. The TSAM, which was meeting performance and signature requirements, was cancelled because cost had grown to US$ 2.3 million. JASSM aims at a much lower cost of less than US$ 0.5 million, while retaining performance, by restricting signature requirements to the frontal arc, and using more recent sensor technology, which reduces costs ($280K for EO sensor with ATR in TSAM to $80K in JASSM).

5.2.6. Electronic Support Measures (ESM)

The use of stand-off weapons alone is not sufficient to give acceptable survivability, in a high-threat scenario, because of the need to approach the target area over hostile territory. On-board defensive aids, like electronic countermeasures and decoys are essential penetration aids. In a dense threat environment, the electronic support measures will require a dedicated aircraft, since they go beyond what can be fitted internally in a strike aircraft or carried in external pods. Thus the defensive systems in a strike aircraft should be adequate for self-protection, without taking too much internal or external pylon space. Raid protection should be entrusted to ESM support aircraft.

5.2.7. Suppression of Enemy Air Defences (SEAD)

A strategic bomber, like the B-1 or B-2, is sufficiently large to carry a comprehensive suite of offensive and defensive systems, as well as a mix of attack and defence suppression weapons, e.g. the SRAM (short range attack missile) for the latter function. Strike fighters are more limited in that respect, although role sharing and specialisation can help, e.g. operating the aircraft in pairs, with one armed for attack and the other for defence suppression. However, a generic strike fighter can never be as effective as a dedicated SEAD aircraft, given the very high-risk of this particular mission. Thus the SEAD and ESM aircraft are essential complements to the strike force in a high-threat environment.

5.2.8. Specialised ESM and SEAD Aircraft

The current ESM aircraft, namely, the EA-6B Prowler, EF-111 Electric Raven and Tornado ECR (Electronic Combat and Reconnaissance), are all adaptations of long-range interdiction aircraft; this is a natural choice, to ensure adequate internal space, survivability and endurance. The only true SEAD aircraft in the west, the F-4G Wild Weasel, uses a fighter airframe for survivability in this high-risk mission, and a two man crew to manage the complex systems. In the present state of defence budgets, it is difficult to find funds to develop small fleets of specialised aircraft, even when the mission is as critical to the survivability of forces as ESM and SEAD.

The SEAD community has reacted to the idea of using single-seat versions of the F-16 or F-15, to replace the two-seat F-4G; the US Navy plans to develop a two-seat version of the F-18F as an ESM aircraft to replace the 4-seat EA-6B. In the interests of economy and survivability the USA and Europe should standardise on a single aircraft, namely a two-seat high-performance fighter, with a SEAD and an ESM version.

5.3. Advanced Short Take-Off and Vertical Landing (ASTOVL)

The V/STOL (Vertical/Short Take-Off and Landing) aircraft has achieved operational status in conditions where CTOL (Conventional Take-Off and Landing) aircraft can hardly operate or not at all: dispersed site and amphibious operations, use of decks of ships smaller than CTOL aircraft carriers. The future replacements of current V/STOL aircraft, if they will exist, will have to be STOVL adaptations of CTOL aircraft, and come closer to CTOL aircraft in terms of flight performance and payload-range. This will represent a significant progress relative to the first V/STOL aircraft, which were once derided as being able to bomb only at the end of the runway.

5.3.1. The Airfield Vulnerability Issue

The motivation for the tens of prototypes of V/STOL aircraft developed in the 60s and 70s, was the vulnerability of airfields to attack with conventional weapons or means of mass destruction. What tended to be overlooked, was that an airfield is much more than a set of runways, and taxiways, it is also a logistic centre.

The development of V/STOL transport aircraft, like the Do31, only served to heighten the realisation of the cost and complexity of operating a dispersed air force. Retaining the air base as a logistic centre, building hardened aircraft shelters (HAS), and using sections of damaged runways and taxiways for take-off and landing, has proven a more practical solution.

5.3.2. Dispersed Site Operations

The logistics of dispersed site operations appears to have been mastered only by the Royal Air Force and the United States Marine Corps, which have devised the means to arm, refuel, camouflage and service aircraft in the field, defend against intruders and saboteurs, manage the operations, etc. These Air Forces continue to use CTOL aircraft for most missions, and reserve V/STOL to cases where the 'penalty' of dispersed site operation is a tactical need or advantage.

5.3.3. Operation from Through Deck Cruisers

The second 'niche' where V/STOL aircraft have found application is to provide naval air cover, strike and reconnaissance, from ships smaller than aircraft carriers, operating CTOL aircraft with catapults for take-off and arrester gear for landing. The larger American aircraft carriers (of the Forrestal, Enterprise or Nimitz classes) with an air wing of 70-90 aircraft displace 60,000 to 100,000 tons, and the smallest ships able to operate CTOL aircraft are in the 30,000 ton class (French Clemenceau and Foch) for Dassault Etendard and F-8 Crusaders, and in the 40,000 ton class (the new Charles de Gaulle) for the Dassault Rafale. For the operation of V/STOL Harriers, ships with 20,000 ton displacement are sufficient, like the British Invincible-class through-deck cruisers. The Spanish Principe de Astúrias, the Indian Vikrant and the Italian Guiseppe Garibaldi are all smaller, but above 10,000 ton.

The logistics support issue does not arise in these through-deck cruisers and larger American amphibious assault ships. The abandonment by the Soviet Navy of the Minsk class through-deck cruisers operating Yak-36 Forger V/STOL aircraft, in favour of the Kuznetsov-class aircraft carriers operating navalised variants of CTOL aircraft like the Su-25 Frogfoot and Su-27 Flanker, suggests that even when facing economic constraints, the greater capability of the latter justifies the extra cost.

5.3.4. The Future Prospects of STOVL

Two decades of successful operation of the British Aerospace (formerly Hawker) Harrier and McDonnell Douglas AV-8, and the probably less successful Soviet trials with the Yak-36, have brought much maturity to the concept of V/STOL operations, and shown that STOVL is the practical solution, because:

- vertical take-off limits the gross weight to less than available thrust, and leads to a poor payload-range and endurance;
- a short rolling take-off, between 100 and 200 m, will give a vast improvement in payload-range and endurance, since all the extra take-off weight is warload or fuel;
- a take-off run of 100 to 200m is available from a through-deck cruiser, and this length can be usually found between craters of a damaged runway or taxiway;
- a rolling take-off reduces ground erosion and aerodynamic interference;
- conventional or rolling landing on a damaged runway, at night or in low visibility, due to smoke or bad weather, is a daunting prospect for a CTOL aircraft, which need not be contemplated for an ASTOVL aircraft;
- without weapons and light on fuel, a vertical landing is feasible, allowing careful selection of a suitable site.

In retrospect, such developments as plenum chamber burning, viz. equivalent to the use of reheat in the fan by-pass flow of the Rolls-Royce Pegasus engine leading to the front nozzles of the Harrier aircraft, was not needed, and could have worsened the problems of ground erosion, hot exhaust gas re-ingestion by the engine, and other undesirable ground interaction effects.

5.3.5. Commonality of ASTOVL and CTOL Aircraft

In the current state of defence budgets in the West, the possibility of development of a dedicated ASTOVL successor to the Harrier can be excluded, on purely economic grounds. In Russia, the Yak-141 prototypes of a supersonic successor to the Yak-36 Forger were not even flight tested. The only chance for a future ASTOVL aircraft to come to fruition, is to have a substantial commonality with an existing major CTOL aircraft programme. Thus it may have been a welcome change that the DARPA (Defence Advanced Research and Projects Agency) ASTOVL project was merged into the JAST (Joint Advanced Strike Technology) aircraft programme, particularly since ASTOVL configuration has been given the lead over the CTOL version, in order to assess a most critical issue: the feasibility of the lift system for STOVL.

5.3.6. Lift Systems for ASTOVL

The controversy in the 60s between the proponents of V/STOL using a single combined lift-cruise engine (Hawker P.1127 Kestrel) and separate lift and cruise engines (French Dassault Balzac and Mirage III-V and German-Italian VAK 191B), was resolved in favour of the former, perhaps not on pure technical merit, but rather on perseverance and determination to make the concept work-out into the only really proven and practical front-line V/STOL aircraft: the Harrier. Comparable performance may have been achieved by the lift plus cruise engine concept, in the Yak-36 Forger, but the development appears not to have been taken to a complete success; the advantage of the lift plus cruise engine for supersonic flight, was not pursued, since the Yak-141 prototypes did not leave the ground. Thus the distinction of being the only supersonic V/STOL aircraft rests with a prototype flown more than 30 years ago: the VJ101C which achieved supersonic flight in 1961. This was a very efficient design, combining twin engines in tilting wingtip pods, for lift and cruise, with a single lift engine vertically in the fuselage behind the cockpit, giving a triangular layout of lift forces (3 post lift system).

5.3.7. The Combined Lift-Cruise Engine

The Harrier demonstrates the penalties of this type of engine configuration:

- the engine is sized for lift, and oversized for cruise (this would not be so much the case for modern highly manoeuvrable aircraft with thrust-to-weight ratios around unity);
- the engine has to be placed at the center of the fuselage, with a symmetric disposition of the 4 nozzles about the center of gravity;
- engine development is constrained by the need to keep the fan by-pass flow thrust to the front nozzles equal to the core engine exhaust flow thrust to the rear nozzles;
- nozzle location in the center fuselage, close to the air intakes, exacerbates hot gas re-ingestion and ground interference effects, countered by the use of flow 'dams', etc.;
- changing an engine, through the top of the fuselage, requires prior removal of the wing;
- the engine has large frontal area, precluding supersonic performance.

It should be kept in mind that every V/STOL concept carriers life-time penalties, and the lift-cruise engine has a unique advantage in its simplicity compared to the use of separate lift and cruise engines.

5.3.8. Separate Lift and Cruise Propulsion

The rationale for this concept is to size and locate the cruise engine as for a CTOL aircraft, minimising fuselage cross-section and leaving the engine at the tail end. Given the high thrust-to-weight ratio of modern fighters, and the benefits of thrust vectoring for agility and control, there is a small penalty for using all that thrust with extra deflection to 90°; in fact nozzle deflection can exceed that value, up 100/110° in a windy condition, to keep the thrust vector vertical for pure lift without sideslip or rolling moments. To make a triangle (or polygon with more than three edges) of lift forces, a separate lift mechanism, e.g. in the fuselage behind the cockpit, is needed. This lift system is a dead weight for cruise, and a lifetime volume penalty due to STOVL, corresponding to the other penalties of the alternative combined lift-cruise engine. There are several concepts for the separate, dedicated lift system, and each has advantages and drawbacks:

- a dedicated lift engine, can have a high thrust-to-weight ratio and be simplified since it operates for a short time, and fuel consumption is not critical; it does add another engine, thereby increasing development cost and maintenance;
- ducting part of the hot high-speed exhaust of the main cruise engine to other parts of the airframe for lift has proved time and again to be unpractical due to high thrust losses in duct bends;
- these high duct pressure losses apply whether the ducted exhaust is used to drive a remote fan (Ryan XV-5), to entrain ambient air (Lockheed XV-4 Hummingbird) or is ejected near trailing-edge flaps (McDonnell Douglas XFV-12);
- to avoid duct flow pressure losses, the remote fan can be shaft-driven, via a mechanical gear box, which incurs another kind of complexity and weight and volume penalty.

The latter two concepts offer thrust augmentation, by entraining ambient air. It is easy to overestimate thrust augmentation and underestimate duct losses. There are examples (XV-4 and YFV-12) of augmentation ratio less than unity, i.e. overall thrust loss. The shaft-driven fan has the advantage that it creates a 'dam' of cold air, which prevents the re-ingestion of hot exhaust gas, which can cause engine stall near the ground. This is one of the two major problems of jet-powered V/STOL aircraft. The other is the suck-down effect near the ground, which can degrade control; there is no easy solution to the latter, since it is configuration dependent, i.e. affected by wing/fuselage shape and nozzle position.

The results of testing of JAST prototypes will be another interesting episode in the long saga of V/STOL concepts since the 50s and 60s. At least there is at present a definite advantage over the dozens of prototypes of the early V/STOL age: a modern control technology able to master the stability problems which plagued early designs.

The results of the JSF competition so far are illuminating to some extent. The McDonnell Douglas design abandoned the concept of ducting high-speed gases half-way through the competition, and changed to a separate lift engine; the cost and logistics of a new separate engine and the ground erosion problems of the hot exhaust, plus installation problems, may have contributed to this being the losing design. The designs selected into the next stage of the competition use a shaft-driven fan (Lockheed-Martin) or a combined lift-cruise engine (Boeing); the latter has, in the hover mode, a downward opening valve, to create an air dam, to prevent hot air re-ingestion. If both design approaches prove successful in hover performance, other issues, like up-and-away flight performance, airframe volume/payload-range and production cost, may decide the winning design. In a sense, incurring the least penalty in overall design, due to the STOVL version, will be a measure of success.

5.3.9. ASTOVL vs. CTOL Issues

The testing of JAST prototypes will answer some interesting questions. The first, and most obvious, is whether the lift-plus-cruise propulsion concept in the shaft-driven fan concept, has at last been brought to the level of practicality of the Harrier, so that its supersonic performance can be exploited. Provided that at least one of the ASTOVL concepts tested in JAST is successful, without an excessive cost penalty, while also improving on the payload-range of the Harrier, it may have a future as Harrier successor for amphibious operations and naval vessels like through-deck cruisers. The CTOL version of JAST will have better payload-range, by using the volume and weight of the lift system in the STOVL version, for extra fuel and weapons. It remains to be seen whether air forces will opt to have a part of their fleet with STOVL capability, or will prefer to take most advantage of internal weapons carriage and extra fuel load of the CTOL version.

5.4. Rotary-Wing and Convertibles

To the vertical take-off and landing capability of V/STOL aircraft, the helicopter adds superior hover performance, which allows better exploitation of terrain masking, when coupled with high agility and a mast-mounted sight. A compromise between the hover performance of the helicopter, and the speed and payload-range of the airplane, is provided by the convertible, at the expense of increased complexity.

5.4.1. Anti-Tank and Air Combat Helicopters

The anti-tank helicopter is reaching a level of sophistication rivalling that of combat airplanes. It has demonstrated high kill ratios against tanks, and proven very effective for night fighting during the Gulf War. The increasing number of armed forces procuring combat helicopters testifies to the growing appreciation of its effectiveness.

5.4.2. Night Flying/Fighting

The night flying and fighting capability of the AH-64 Apache was exploited to advantage during the Gulf War, against an enemy ill equipped to detect the impending threat. The use of IR sensors for navigation and targeting is well established, as well as that of night vision goggles. Yet there is a lack of standards to predict what kind of resolution the night vision system must have, to allow safe nap-of-the-earth flying in given weather conditions, or to give reasonable assurance of identification of a target in a given background. The large investment in night flying and fighting equipment, justifies further research into its safe and effective use.

5.4.3. The Mast-Mounted Sight

Although the helicopter is by army standards a soft-skinned vehicle, vulnerable to splinter burst of most gun shells, its has achieved high kill ratios through terrain masking. The Mast-Mounted Sight (MMS) is an important element, in allowing observation of the battlefield, with minimal exposure.

5.4.4. Agility and Nap-of-the-Earth Flying

Agility is also an important element, in allowing a helicopter to emerge quickly from covert observation, to fire fire-and-forget missiles, and regain cover in a short time. Agility also benefits nap-of-the-earth flying, to gain an observation or firing position, without prior enemy detection. Last but not least, high agility will enhance the capability of the combat helicopter for self-defence and as an anti-helicopter weapon.

5.4.5. Size, Weight and Warload

An interesting comparison can be made between the American AH-64 Apache and the Franco-German Tiger, in that they have comparable engine power, but the latter is smaller and lighter. The Tiger's greater agility was apparently rated second to the greater warload of the Apache (16 instead of 8 anti-tank missiles), in the evaluation by the British and Dutch armed forces, which led to the selection of the Apache in preference to the Tiger. The preponderance of modern helicopter technology is shown by the much lower ranking of other contenders, like the AH-1 Cobra. The Augusta A.129 Mangusto proved too small to carry effective mission systems. The Russian Mil-28 Hind and Kamov Ka-50 Hokum may give an example of too much resources spent on airframes, and too little left to develop mission systems. The development of two systems for the same mission is a luxury, which the former Soviet Union might have been able to afford but hardly Russia. Another example of division of resources hampering a rapid and complete development of the helicopter and its weapon system is the European scene, with the Franco-German Tiger and Italian Mangusta, and other countries opting for an off-the-shelf purchase (Apache for Britain and the Netherlands) - a lost opportunity for standardisation or an European programme.

5.4.6. Millimetre-Wave Radar and All-Weather Capability

The millimetre-wave (MMW) radar (Longbow) fitted to the Apache AH-64D, is a costly extra which enhances all-weather, as distinct from just night fighting, capability. The US Army has adopted a mixed fleet approach, where Apaches not fitted with Longbow may receive information from those so-equipped. The British Army took a different option, reducing the number of helicopters procured but having the Longbow MMW fitted to every of them. The contrast of the two choices is an interesting case of cost vs. effectiveness comparison.

5.4.7. Helicopter vs. the Convertible, e.g. Tilt-rotor

A convertible, like a tilt-rotor, but not a tilt-wing, would retain the ability to fire weapons from wing hard points, in hover. The convertible tends to have degraded hover performance when compared with a helicopter, and this would be a serious drawback for the anti-tank mission. The exploitation of the higher speed capability of the convertible in airplane mode, would come at the loss of the nap-of-the-earth flying capability, which gives the helicopter superior terrain masking and survivability.

5.4.8. Naval, Transport and Rescue Roles

The superior payload-range and speed (or productivity) of the convertible have a pay-off for other helicopter missions, such as:

- search and rescue of downed aircrew over enemy air space;
- logistic transport as replacement for medium helicopters;
- naval roles, such as anti-submarine warfare, mid-course guidance for ship-to-ship missiles, search and rescue over the sea;
- battlefield surveillance and airborne early warning, the latter also applying to ships of the through-deck cruiser class.

The increased productivity of the convertible, in terms of speed and time to reach operating location, and area covered by its larger payload-range, must be weighted against the effects of greater complexity, in terms of acquisition and operating cost.

5.4.9. Medium and Light Helicopters

Whereas the convertible may be an alternative to the medium helicopter, the pure helicopter will remain supreme in the lightweight class, for scout and observation, casualty evacuation, and other roles demanding good hover performance with a modest payload. Fitting unguided rockets, fire-and-forget anti-tank missiles, and air-to-air missiles in medium (e.g. UH-60 Blackhawk) or some light (e.g. OH-6 Cayuse) helicopters is feasible, but these will lack the mission systems to exploit the full potential of such weapons, in particular at night and in bad weather.

The US Comanche has proven that stealth technology can be also applied in the difficult case of the helicopter, including reduction of RCS from the rotor head, by fairing over part of it, and using helical scattering around the rotor hub. The use of composites for the blades benefits stealth as well as ballistic resistance to small arms fire. The canted body panels appear to offer little degradation in flight or hover performance or fuselage volume.

5.5. Unmanned Air Vehicles (UAVs)

All projections on the future evolution of air power, point to an increased use of unmanned or uninhabited air vehicles (UAVs). The reasons are that, as the vulnerability of fighters to air-to-air and surface-to-air weapons increases, and casualties and prisoners become a less acceptable adjunct to military operations, the trend will be to transfer the higher risk missions from manned to unmanned aircraft. Unmanned aircraft will be remotely-piloted, rather than autonomous/automated, to retain some of the flexibility of the human operator. The latter is the only advantage of the manned vs. unmanned aircraft; in every other respect, like agility, size, cost, etc. the UAV is a better choice for every mission where human presence is not essential. This justifies giving particular attention to this class of vehicle, which will have an expanding role in the future, making use of aircraft technologies in a different way.

5.5.1. From the RPV to the UAV/UTA/UCAV

The modern concept of UAV has its roots in the missile as totally automated vehicle, and RPV (Remotely Piloted Vehicle), but goes much further. It attempts to combine the qualities of the autonomous vehicle with the judgement of the remote pilot, i.e. all routine flying and mission tasks are automated, leaving to the remote pilot only critical decisions like: target identification, authorisation of weapon release, damage assessments, declaration of mission complete or mission abort, selection of a different objective, change of mission planning, etc. This design and operational philosophy is better reflected by the designations Unmanned Air Vehicle (UAV), or Uninhabited Tactical Aircraft (UTA) or Unmanned/Uninhabited Combat Air Vehicle (UCAV).

5.5.2 An Expanding Range of Missions

For missions where the intelligence, flexibility and adaptability of the human operator is essential, the replacement of manned combat aircraft by autonomous/automated UAVs cannot be contemplated. The case is different when comparing a manned aircraft (more precisely a locally manned aircraft) with an Unmanned Air vehicle (UAV). The UAV can be as effective as a locally manned aircraft (LMA), provided that the remotely located pilot can be given the same situational awareness as a pilot in the aircraft, and has similar means of control. In this case the remotely located pilot is a preferred option, since he can 'fly' the aircraft from a safer location, unexposed to physiological effects of hard manoeuvring, and vulnerable to mental but not the physical stress of combat.

Creating, for a remote pilot (in the ground, in the air, anywhere), the same situational awareness he would have when flying in the aircraft, is a matter of advancing mission systems technology to the point where:

- on-board sensors achieve a resolution which dispenses with direct use of human senses, like vision;
- all the sensor information can be transmitted in real time to the remote pilot;
- the commands of the remote pilot can be sent in real time to the aircraft, and the reactions of the latter sensed back also in real time.

At present, it is only for a limited spectrum of missions that a remote pilot can be almost as effective as a pilot in the aircraft. One case is surveillance, when most of the data cannot be analysed on board anyway. For surveillance missions requiring on-board analysis of data, or intelligent adaptation of the mission profile, manned surveillance aircraft, like J-STARS are needed, and have to be operated at stand-off distances from enemy defences. High-risk missions, like surveillance deep into enemy airspace, have to be relegated to autonomous UAVs or RPVs.

As sensor capabilities, data link capability, and computing speeds, advance, more missions become accessible to UAVs, such as reconnaissance, and strike. Thus the division of tasks between manned and unmanned aircraft tends to shift with time in favour of the latter.

Air-to-air combat is likely to be one of the last missions to be assigned to a UAV, given the very dynamic situation and the importance of motion cues and perceptions which are difficult to simulate realistically. Missions like electronic support and defence suppression favour UAVs, if the dynamic elements can be dealt with, since they are high-risk, and also a complement of deep strike and interdiction.

It should be noted that automation of routine flying, navigation and mission tasks, and extensive exchange of data with other vehicles to improve situational awareness and mission effectiveness, will apply both to locally and remotely manned aircraft; the UAV will need to exploit these technologies to a greater extent than the LMA, i.e. as these technologies mature, more missions will be transferred from LMAs to UAVs.

5.5.3. Advantages of the UAV Design

Once it becomes possible to give the remote pilot the same situational awareness and control authority as a pilot-in-the-aircraft, the UAV has nothing but major advantages:

- removing the pilot dispenses with the cockpit and associated life support systems;
- the cockpit gives a lower limit to fuselage cross-section, and then aerodynamic fineness ratio specifies minimum length, so that deletion of the cockpit allows for a smaller vehicle in every dimension;
- thus the UAV has a smaller radar cross-section, and can be made stealthier also in other respects, e.g. having a smaller engine, with reduced IR emission;
- unconstrained by the physiological limits of the pilot, the UAV can be designed to much higher g, limited only by engine power and structural strength;
- since there is no human life on board, the systems in a UAV need not be as redundant or reliable, allowing further reductions in cost and complexity;
- a UAV can be used in high-risk missions, since there is no prospect of loss of human life or the taking of prisoners;
- a UAV is more amenable to low-cost, semi-automated maintenance and operations;
- a UAV fleet has lower life-cycle cost by greater use of simulation and less actual flying in peacetime.

These factors and their implications in design, will be considered next.

5.5.4. Benefits of Absence of the Cockpit

The cockpit, including structure, ejection means, life support, controls and displays, contributes about 1000 lb to the weight of a single-seat fighter, and about twice as much to a two-seat aircraft. Taking an F-16 as reference for the former and an F-15E for the latter, the cockpit represents about 5-9% of empty weight, and less than 10% of aircraft cost. Its replacement by fuel would increase internal fuel tankage by 10-20%, with a corresponding increase in range. While these benefits are not negligible, they are far short of what could be achieved by designing the aircraft as a UCAV rather than a LMA. Thus, removing the aircrew from a LMA, when automation and communication technologies mature, would have as main benefits, avoiding exposure of the crew to casualty or capture, and making it difficult to prove the origin of a downed aircraft.

5.5.5. Reduced Size of the Airframe

The cockpit(s) for the crew puts a lower limit on the size of the airframe, because:

- it sets a minimum frontal area, for comfortable crew performance, adequate visibility, sufficient panel space, safe ejection, etc.;

- a good aerodynamic design requires a fuselage fineness ratio of about 10:1, thus, setting a lower limit to fuselage length;
- the fuselage dimensions determine volume, hence wing size, propulsion needs, and eventually aircraft weight and cost.

Removing the crew eliminates these lower limits, and allows the design of a smaller vehicle, if other requirements do not require a similar size of vehicle. If, for example, the payload-range is not reduced, then this, not the cockpit, becomes the size and cost driver, and not too much is gained by the UAV design, e.g. a UAV with the payload-range of an F-16 or F-15 will not be that much smaller or cheaper, perhaps 10 to 20%.

The advantage of the UCAV is that, if payload-range requirements are reduced, then it can be made much smaller than an LMA, because there is no crew to keep size up. Thus a UCAV would benefit greatly from weapon miniaturisation, more than an LMA. If an internal payload of 2000 - 4000 lb was acceptable for a subsonic UAV with a radius of action of about 400 miles, then it could probably be designed for half the weight and cost of a supersonic F-16.

5.5.6. Improved Stealth Features

The high-visibility cockpit of a modern fighter is hardly a stealth feature, and the forward location of the cockpit limits the utilisation of internal space. A UAV can have a stealthier shape, and make better use of internal space, increasing the benefits of smaller size, as long as payload requirements remain moderate, say 2000 to 4000 lb. This payload could be sensors in a RSTA (Reconnaissance, Surveillance and Target Acquisition) mission, weapons in a strike mission, or a combination of both for SEAD (Suppression of Enemy Air Defences).

5.5.7. Increased Manoeuvrability and Survivability

The smaller size and improved stealth of the UAV would improve survivability; another contribution would be the increased manoeuvrability due to the elimination of the physiological limits of the pilot. The latter can endure at most 9g, allowing escape from an AAM or SAM with a 27g turn capability, but making it impossible for an aircraft to out-manoeuvre a missile using TVC to pull say 35g. In principle, a UAV could be designed to defeat this, by taking a limiting load factor of, say, 12g, with a moderate structural weight penalty. Much larger load factors would penalise the UAV design, but the 40g missile design to defeat it would also be penalised. Ultimately the missile might win a g-race, at a non-negligible increase in cost, complexity and weight, which would be an indirect improvement of the survivability of the UAV compared to the LMA.

5.5.8. Lower Reliability Standards

Since a UAV is not man-rated, it does not need to have all the fail-safe, back-up and reliability features of a LMA. The reliability and redundancy could be degraded to the level needed to ensure high probability of accomplishing the mission, rather than saving the crew. Thus the level of redundancy could be lower, and a lower standard of equipment, maintenance and dispatch criteria would apply. This would reduce both production and maintenance costs, and the support man-power. However, the main benefits to life-cycle costs (LCC) would come from semi-automated maintenance and operations and reduced peacetime flying.

5.5.9. Semi-Automated Maintenance and Operations

The potential exists to apply automation not only to the flight vehicle itself, but also to operations and maintenance. This would reduce the support personnel needed to arm and refuel the aircraft, and perform scheduled and unscheduled maintenance. This is a major factor of operational cost. In principle, semi-automated operations and maintenance can apply both to LMA and UAVs. However, the latter can take greater advantage of the concept, due to its simpler design, lesser reliability requirements and lower dispatch standard. The biggest contributor to reduce LCC would be reduced flying hours, implying a smaller ground crew and reduced maintenance effort.

5.5.10. Reduced Peacetime Flying

The operating costs of a fighter squadron in peacetime are driven by the need to maintain pilot proficiency through actual flying. A pilot should fly 30 hours per month, or at least 18 h, by NATO standards. This sets the minimum flying time for a squadron in peacetime, the fuel and the space it consumes, the size of the ground crew, the area of hangars, maintenance and armament facilities, etc.

In the case of a UAV, since the pilot is not in the vehicle anyway, it could be trained without flying the aircraft. The concept of keeping the UAV in storage with just minor checks, and training the pilots in a simulator, is attractive in that it would allow the UAV to be designed for wartime flying (a few hundred hours) instead of peacetime flying (a few thousands hours), perhaps even allowing maintenance free design, due to the reduced lifetime. This extreme concept is unlikely to satisfy military planners and political authorities, no matter how much they would appreciate the economies made thereby. Neither would relish the uncertainty of not finding out until an emergency arises, whether the stored UAVs were really flyable and the pilots proficient – if they were not, a quick fix might not then be available.

Although it could be technically feasible to store UAVs in good conditions for one or more decades, in practice updates would have to be made every 5 to 10 years and tested for their effectiveness. This suggests a compromise between the fighter squadron flying all aircraft in peacetime, and the UAV squadron keeping all vehicles in storage. As an example, suppose one-fifth of the UAV fleet was brought out of storage every year or two, so that the whole inventory would be rotated every 5 to 10 years. The pilots would still fly 30 h plus per month in the simulator, but would also fly 6 h with the real UAV, to make sure that, "simulation was still like the real thing", or that they had not developed simulator tactics that did not work in real flight. The maintenance and support personnel could be one-fifth of the wartime complements, and would be trained on the "real thing", so as to be able to instruct the four-fifths extra staff needed in wartime. The flying period every five to ten years, could be used to test upgrades to the UAV, and to make sure that fleet was really in operational condition.

5.5.11. Lower Life-Cycle Costs

The preceding discussion points to the main advantages of the UAV in terms of life-cycle costs:

- for a moderate payload of 2000 - 4000 lb, size and costs could be halved relative to a LMA;
- wartime surge capability could be kept with full pilot complement and one-fifth support staff, leading to about 1/3 of operating costs.

Thus the UAV offers a unique opportunity to break the upward cost spiral of aircraft, while avoiding all risk to pilots, and improving survivability, it is clear that the UAV will tend to be preferred to the LMA in the future, for all missions which it can perform adequately.

5.5.12. Combined Manned-Unmanned Operations

The shift of missions from manned to unmanned aircraft will be limited by several factors:

- it is not affordable to replace the existing manned fleets, and it will remain more cost-effective to continue to upgrade them for some time;
- automation and telepresence technologies will not mature fast enough to replace manned aircraft by UCAVs except in simpler missions;
- at least one more new generation of manned aircraft will be needed in any case, for the more complex missions.

The gradual shift of missions from manned to unmanned aircraft means that for the foreseeable future, even beyond 2020, combined operations will be the rule:

- UAVs, of autonomous type, like missiles, will play the role of stand-off weapons, with pre-programmed cruise and terminal guidance;
- UAVs, in the sense of UTAs and UCAVs, will undertake high-risk missions of increasing complexity, like surveillance and strike of heavily defended areas;
- manned aircraft will perform the most complex missions, at increasing stand-off distances, to protect their crews.

Having to divide the declining defence budgets between (i) upgrading existing manned aircraft, (ii) developing a new generation of fighters, and (iii) introducing UAVs for some missions, will imply that the transition from manned to unmanned operations may be slower than the maturation of relevant technologies, like automation and telepresence, and investment decisions in the three options may become increasingly difficult to make.

5.5.13. A Large UAV Carrier or Mixed Force

A concept has been suggested of a large UAV carrier, able to launch and retrieve UAVs from bomb-bay type doors or eject them from a rear loading ramp opened in flight; this large UAV carrier would loiter away from heavily defended areas, leaving to UAVs the last few hundred miles of penetration. The release of a UAV from a bomb bay, like a missile, or from a canister ejected from a rear ramp, should not be a problem, but retrieving it, say, on a trapeze and hook-up mechanism, is another matter. In the early post-war years a similar, but less ambitious, design was considered: a small self-protection fighter, to be released and retrieved by a B-36 mother-plane, using a trapeze. Tests using a B-29 mother-plane, showed that turbulence and aerodynamic interference made hook-up very difficult. In one case the pilot had to land back at Edwards AFB, where the flight tests were being carried out, after trying to hook up for half an hour, without success. It is an open question whether modern control technology could overcome this problem, since the aerodynamic interference with the mother ship may be strong, and exceed available control power, with risk of collision of the two vehicles. These problems are alleviated if hook-up to the mother plane occurs on a long trapeze, like an in-flight refuelling probe. In this case it would appear simpler just to develop air refuelling for UAVs, since in this case the UAV stays behind and below the tanker, avoiding the worst aerodynamic interference. This would use existing tankers, and would not require a costly and vulnerable mother ship. Command and control would use existing AWACS and JSTARS, rather than putting too many assets in a single mother ship.

In conclusion, comparing the options: (i) a large UAV carrier with AWACS/JSTARS functions, versus (ii) using a distributed mixed fleet of existing tanker/AWACS/JSTARS/fighter fleets plus new UAVs with air-to-air refuelling, the latter is superior in terms of (a) lower risk of development, (b) lesser cost and (c) reduced vulnerability, because:

a) whether or not the control, aerodynamic and flight control problems of retrieving an UAV in flight into a mother ship can be overcome, it will be much easier to develop in-flight refuelling for UAVs, since in that case aerodynamic interference problems are much less severe;

b) the large UAV carrier/command aircraft would be costly to develop and produce and duplicate existing capabilities in other platforms, whereas it would be much cheaper to use existing tanker/AWACS/JSTARS/fighter fleets, concentrating the scarce available resources on the new elements: the UAV, its in-flight refuelling capability and distributed command and control of the mixed fleet;

c) the few UAV carriers would have a large signature and be high value targets, justifying massed attack by simple weapons (conventional AAMs/SAMs) or selected use of sophisticated weapons (e.g. a hypersonic SAM), whereas the distributed mixed fleet of tanker, AWACS, JSTARS, fighters and UTAs would be more survivable and flexible in use.

The large UAV carrier (i) would have the advantage of long-range, near-global deployment, independent of ground support, with less in-flight refuelling. However, the large airborne UAV carrier, like the large naval aircraft carrier, is not completely defended by its own aircraft, and might need a fleet of escorts; these would need to have the same global reach as the large carrier, otherwise the independence for local ground support would be lost. The operation of the large UAV carrier alone, relying entirely on self-protection of the mother ship by its baby UAVs, might be too high risk, because it will be a long time before the latter are adequate air-to-air fighters; this is the most difficult mission for a UAV. The eventual shooting down of the large UAV carrier would be a major embarrassment, especially as regards the loss of human life; this is precisely what UAV operations were supposed to avoid. Thus the concept of the large UAV carrier needs to demonstrate (i) affordability, (ii) survivability and (iii) the ability to safely and efficiently retrieve UAVs into the mother ship.

5.5.14. Location of the Pilot Station

The pilot station of a UAV would not be on board, but rather (a) on the ground, (b) seaborne or (c) in another airborne platform. The ground station would be the cheapest and easiest implementation, because it could use off-the-shelf commercial equipment, without constraints on volume, weight, power consumption, electromagnetic interference (EMI) or harsh vibration or corrosion environments. Thus the ground based UAV pilot station is likely to be the first to be implemented. For combined operations of UAVs with carrier-borne manned aircraft, the remote pilot station should perhaps be placed in a ship, so that some constraints on space, weight, etc. would come into play. They would be more severe in the case of a UAV pilot station in another airborne platform, e.g. a large UAV carrier, an AWACS or JSTARS aircraft, or a fighter aircraft. In the latter cases, integration of the UAV pilot station into the host platforms (naval or airborne) would be a major task, over and beyond making sure the station functions as intended on its own.

5.5.15. Risks of Proliferation and Misuse

Since a UAV is under remote command, the possibility of an opponent taking over the vehicle cannot be excluded; the UAV design should include several security measures, plus a safe return to base mode, which ignores all other commands. In this case only an opponent with comparable information warfare capabilities could take-over the vehicle or divert its mission. Jamming and disrupting data links and attacking UAV control stations would be other options, less demanding of 'clever' use of information. A distributed communication network and scattered command centres would add to the cost of UAV operations, but make the ground or remote elements less vulnerable.

The other risk is the use of UTAs by rogue regimes or even terrorists. The basic technologies are or will be commercially available. The most difficult design aspect of an UTA, is to ensure sufficient control for the remote pilot, to be able to use his moral judgement, e.g. to identify the target, authorise weapons release, more sure there is no significant collateral damage, etc. A terrorist group would not have such concerns, and could use an UTA as an area weapon, in which case it could do with less advanced technology; this means that the risks of proliferation are a greater concern for UTAs, than for a modern manned aircraft, which require a larger development and support infrastructure.

5.5.16. Long-Term Trends and Consequences

Some argue that the LMA will exist forever, because the judgement, flexibility and wisdom of the human being will always be needed on-board, for some sensitive missions. However, when the stage is reached, where nearly all missions can be performed by UAVs, will that argument suffice to justify the costly development of a small fleet of very vulnerable manned aircraft? It may be that the UAV will ultimately take over, when it out performs the LMA for most missions, and the latter becomes more of a liability than an asset.

Although a total shift to entirely or predominantly UAV operations can occur only well after 2020, it may be worthwhile to mention briefly some of the potential consequences. The performance of military operations solely or mainly by UAVs may lower the threshold of conflict, since there is no risk of human casualty, which is a traditional cause for embarrassment and carries the potential for retaliation and escalation. It becomes possible for potential enemies to test each other's strength, before committing to an offensive operation with casualties or territorial gains.

6. AFFORDABILITY OF FORCES

The affordability of airborne forces can be maximised by three complementary measures: (i) operating the minimum number of distinct aircraft types; (ii) achieving the lowest life-cycle cost for each of them; (iii) phasing upgrades of existing aircraft, and replacement by new designs, in an optimum manner.

6.1. Design for Low Life-Cycle Cost

Although much of the expenditure with an aircraft fleet occurs later in the life-cycle, in the operational phases, the programme cost is determined early on, at the requirement and design stage. The appreciation of this fact is the key to affordable aircraft, and can avoid later degradations of performance in pursuit of elusive economies.

6.1.1. The Elements of Life-Cycle Cost

The elements of life-cycle costs are all stages of the development and operation of an aircraft:

- the studies, simulations and scenarios leading to the establishment of specifications;
- the preliminary studies and design trade-offs, to meet the requirements;
- the development tests, e.g. in wind tunnels, ground rigs, flight simulators, to reduce technical risk;
- the full-scale tests, e.g. flight testing, use of instrumented ranges, to verify performance guarantees;
- the operational trials by leading service units, to establish most effective tactics;

- the regular operation by service units, including training, maintenance and mission planning;
- the phased introduction of upgrades to meet growing threats or changing or additional requirements;
- the development of new or improved versions.

6.1.2. Actual vs. Committed Expenditure

The early stages of the life cycle involve little expenditure relative to the operational phase, perhaps no more than 10% of the total life-cycle cost. Yet it is at this early stage that the aircraft design is frozen and most of the programme cost is committed, perhaps as much as 90%. As shown in Figure 6, 90% of the programme cost may be frozen, when only 10% of the funding has been spent.

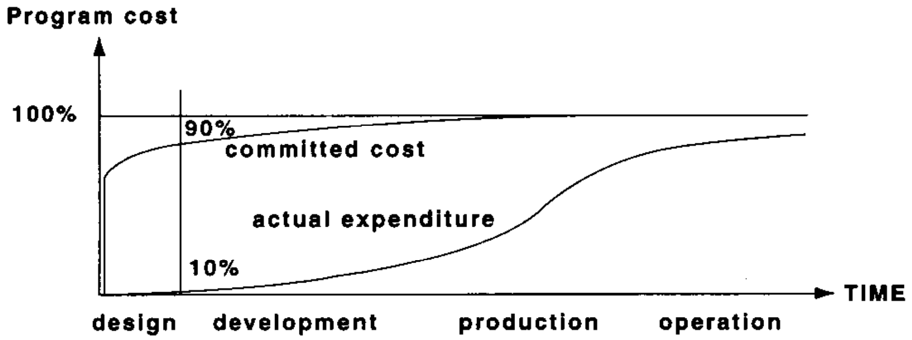


Figure 6 – Comparison of committed cost vs. actual expenditure over lifetime of a program

6.1.3. Degradation and Elusive Savings

The awareness of the life-cycle cost of an aircraft tends to become more acute at the later stages of production, service entry or operation. However, even before production, at a late development stage, there is little that can be saved by partial changes to an already frozen design. The partial cut-backs can result in an unbalanced aircraft, with severely degraded capability. The expected savings will be small, and may fail to be achieved, due to the cost of the changes and time delays they introduce. Disrupting the technical pace of a programme, or stretching it over time, tends to drive up cost. There are examples of degraded capabilities which brought in the end cost increases.

6.1.4. Flexibility in Setting Requirements

The drive for affordability must start right at the beginning of the life-cycle, at the requirements stage. The requirements should be set before the point of diminishing return, which may not be too far from what is ultimately achievable on available technology, but will cost much less (Figure 7). Since the military planner may not be aware of the small details of the cost vs. capability curve, he should specify requirements as a range of values, and give priorities or incentives where he sees the greatest operational benefit.

In this way the designer can play with available technology, to achieve the greatest operational capability at lowest cost and risk. This will allow the assessment of a variety of configurations at the preliminary design stage, to establish the most promising baseline.

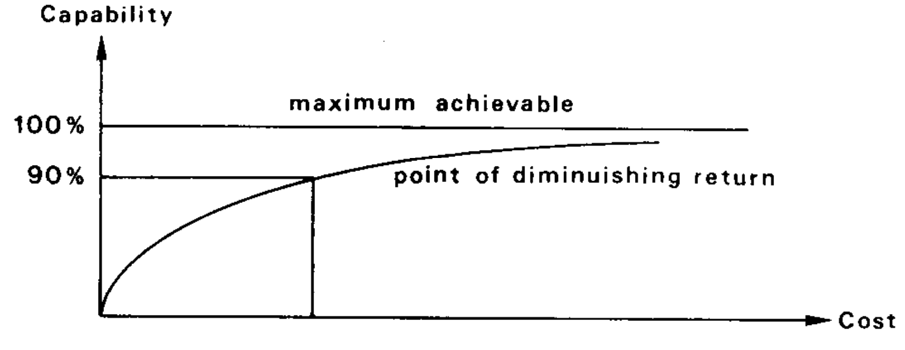


Figure 7 – Comparison of cost versus achievable capability

6.1.5. Preliminary and Frozen Design

The most critical stage to affordability occurs long before major hardware has been built, tested or flown, at the detailed design stage, before the final configuration is frozen. At this stage it is critical to take into consideration the cost drivers along the whole life cycle:

- the technologists provide the range of options within the stage-of-the-art;
- the operational requirements give priorities for the choices;
- the production and maintenance teams make sure the design is 'friendly' from their point-of-view.

Ensuring cheaper production and easier maintenance at this stage is much more effective than trying to make late changes when hardware has been produced.

6.1.6. Concurrent Engineering Design Practices (CED)

Concurrent design practices will reduce production cost and time, reduce parts inventory and make possible economical low-rate production. It will have also benefits in reduced spares inventory, shorter maintenance man-hours, and higher availability; all of the latter need to be proved by testing, much like other performance objectives.

6.1.7. Integrated Product Development (IPD)

Integrated product development or concurrent engineering reduces the risk in product development by introducing knowledge early in the programme, before large scale resources are committed and when the flexibility to use better information is greatest, and the cost of making changes is lowest (Figure 8). Thus IPD/CED reduces late and costly change by looking early on at design options, and their implications over the life-cycle of the product.

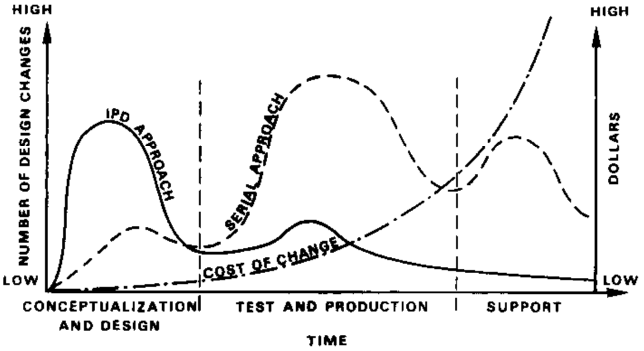


Figure 8 – Program outlay as a function of time for distinct development strategies

6.1.8. Breakdown of Program Costs

The following is a breakdown of the major components of program costs, averaged over a number of different US programs, for the distinct services and various missions.

Program phase	Percentage of total cost	Period of expenditure (years)	Outlay per year
Research Development, Test and Evaluation (RDT&E)	6%	6-10 yr	0.6-1.0%/yr
Production and Procurement (P&P)	54%	8-20 yr	2.7-8%/yr
Operations & Support (O&S)	40%	20-30 yr	1.3-2.0%/yr

Table VI

Breakdown of Aerospace Program Costs

This breakdown is strongly dependent on what is included in each category, and is modified by aircraft and systems upgrades.

The operations and support are a significant fraction of LCC, but since they are spread out over the longest period, the yearly outlay is not the highest. The O&S costs tend to be treated as long-term; standing budgets have tended to have all costs more closely scrutinised, and trade-offs between reducing the inventory to afford the development and production of new types are increasingly necessary.

The research, development, test and evaluation phase is by far the smallest cost item, and also the lowest yearly outlay. In spite of this, it is the most vulnerable, for several reasons:

- a new programme tends to have a closer scrutiny than an established one: do we really need it?
- a partially unproven design is more open to doubts and scepticism: will it work?
- it is relatively 'easy' to cancel a programme before much has been invested into it: is it worth the cost?
- there may be the perception that cancelling a programme now will avoid a budget crunch later, yet existing systems may be more costly in O&S;
- the argument that improving an existing design is cheaper and almost as good can be difficult to disprove: is the new programme that much better?
- competition for scarce funds between very different and unrelated projects can lead to odd comparisons: which should be built, viz. new fighters, more stealth bombers, aircraft carriers, new nuclear submarines, battle tanks, convertibles, anti-tank helicopters, satellites, new generation infantry weapons, improved artillery, etc. if not all can be afforded?

The production and procurement is the largest cost item, and usually also the largest yearly outlay. Yet, cancellation at this stage can be quite embarrassing, since it appears to be a waste of RDT&E funds, unless the technology can be re-used in a new, replacement programme. Arguing that the next attempt will be more successful technically or financially may not be easy, unless there is a compelling need for the system. The problems at this stage may be:

- cut-back in numbers to reduce total cost;
- delay in production build-up, to ease budget shortages;
- production stretch-out, to reduce yearly outlay.

Often these are short-term economies, at the expense of increased total costs. Alternatively, a squeeze between O&S, P&P and RDT&E costs, may tend to victimise new programmes.

6.1.9. Components of RDT&E Expenditure

The listing of the main components of RDT&E expenditure points to the areas offering greater potential for cost reduction:

- Avionics Development: 30% of the R&D cost (note that means it is 1.8% of system LCC). This is the largest single component of development cost and can clearly benefit from two areas for potential reduction: (1) maximum utilisation of simulation and modelling to ensure that the avionics suite specified meets known mission requirements and no more; and (2) maximum integration to ensure shared functions with minimum hardware expenditure. Much of the avionics development work can and should be handled within a synthetic environment as opposed to being conducted on the aircraft.
- Airframe Development: 12% of R&D cost. The utilisation of modelling and simulation is perhaps best known here. Wind tunnels and flight simulators are historically applied to aircraft development. However a primary piece of development work which has only minor impact on development cost (in fact may increase development slightly) is design for production and multi-mission capability. This capability however, as we will discuss later, has major impacts on production cost. Since production cost remains the primary component of LCC (over 50%), the savings here represent far greater value than the expenditure during development. This is a primary area for prudent investment during R&D which can yield major cost savings later.
- Propulsion: 6% of R&D cost. The most obvious way to save is to use either an existing engine or a derivative. Given the much longer development cycle for engines than airframes it is also a safety advantage to utilise a derivative engine since engine reliability tends to improve with service. This is especially true with single engine aircraft designs.
- Flight Test Aircraft: 20% of R&D cost. This is the second highest share of R&D cost, representing significant programme investment. Clearly utilising simulation, modelling, and advanced test techniques which allow fewer test aircraft to be purchased represents a significant potential savings to the programme.

6.1.10. Predominance of Production/Procurement

The Production (Procurement) portion of LCC cost represents the largest single share of the total programme investment. Over 50% of total LCC has historically been consumed during production/procurement. The largest cost share of the production portion of LCC is the allocation to recurring flyaway cost. Over 80% of the production cost (above 40% of total LCC) is consumed by this element.

In the area of production cost the three principal elements are airframe, avionics, and propulsion. However airframe costs represent nearly 50% of the total recurring flyaway production cost. This fact illustrates why designing the airframe for ease of production and/or modular design to allow multi mission capability with many common components has such significant impact. Over 20% of the total LCC of the entire system is represented by the recurring flyaway production cost of the airframe. The next highest contributor, at over 15%, is the recurring fly away procurement costs of the avionics. No other single elements within LCC come close to these percentages, save the total cost of mission personnel (around 13% counting both officers and enlisted).

6.1.11. Some Cost-Cutting Options

In summary, as can be seen from the above, investment in reducing the cost of manufacturing the airframe (both direct labour and materials) is the single largest cost leverage available to the designer. Other key points for lowering LCC are:

- Utilising an existing or derivative propulsion system in the new airframe (Note: also increases safety);
- Minimising the number of Flight Test Aircraft in the Development programme;
- Maximising the use of modelling, simulation, and synthetic environments in Avionics development;
- Reducing the recurring fly away cost of avionics through using COTS (commercial off the shelf) hardware; software re-use; and eliminating unnecessary requirements.

This advice of experience may need to be adapted to recent trends, e.g. RDT&E costs have grown in relative importance, especially for short production runs. Also, some pieces of advice need to be applied with caution and judgement, e.g. using an existing up-to-date high-performance engine is a major time and cost saving, e.g. the J-79 in the F-4, the F-100 in the F-16, and probably the F-119 in the JSF; however, forcing a less than ideal engine into an airframe for 'quick and cheap' development may turn into a lifetime handicap, which it may never be possible to fully correct, e.g. the limits of the TF30 harmed the F-14 A/B agility and reliability, and re-engining with the F-100/F-110 generation in the F-14D was never implemented on a fleet-wide scale.

6.1.12. Principles of LCC Cost-Reduction

The following summary of principles of LCC cost-reduction includes both topics discussed in the present section and examples from other sections:

- take into account, at the design stage, both production and operation costs (6.1.1 - 6.1.2);
- give a margin of flexibility in setting requirements, to allow the most cost-effective design compromise (6.1.4);
- design for open avionics and software architectures, so that new weapons, hardware and missions can be integrated with minimum change, i.e. reduce the cost of upgrades (6.4);
- use integrated product development to minimise production cost and spares inventories (6.1.6 - 6.1.7);
- introduce new and advanced technologies only when their extra cost and risk is outweighed by performance and/or reliability improvements;
- go for the simplest design possible, with maximum use of off-the-shelf equipment, unless a new development is justified;
- use simulation and synthetic environments to compare alternative designs and minimise costly testing;
- invest wisely in improved reliability and maintainability to reduce support and operation costs (6.2);
- design aircraft families to perform multiple roles, with maximum commonality and minimum change between variants, e.g. the new generation fighter family (7.1 - 7.10);
- shift the simpler missions to less costly platforms, e.g. replacing manned fighters by UTAs (5.5), when possible;
- exploit the benefits of modular design, to minimise the number of types in service (7.11);
- take advantage of commonalties with the civil sector, e.g. for whole transport aircraft or for computing, avionics or system components.

6.2. Testing, Maintainability and Availability

Life-cycle cost and operational effectiveness are affected by the usual set of five 'abilities': availability, reliability, maintainability, supportability and interoperability (another two 'abilities', affordability and survivability, are dealt with respectively in the preceding and following sections). The five abilities need to be demonstrated by testing, much as flight or systems performance.

6.2.1. Consolidation of Test Facilities

Model scale testing takes up a considerable fraction of the development time and effort. Major test facilities, such as wind tunnels for high Mach or Reynolds number capability and large cross-section, or flight simulators with large amplitude of motion and high acceleration capability, are expensive to build, support and operate. The consolidation of such facilities, at times of declining defence budgets and reducing numbers of aircraft development programmes, can increase utilisation of the facilities retained in operating condition, and free funds for their upgrading and eventual replacement.

6.2.2. Internetting of Test Ranges

Full scale testing is a major fraction of development cost, and can use a number of flight test and weapons ranges. Some modern systems are so complex, that realistic testing requires internetting of test ranges. In cases where real time coordination of all test elements is difficult, some may be replaced by test data records taken earlier or by simulation.

6.2.3. Simulation in Support of Testing

Simulation can make a major contribution to reducing the cost of testing, in several ways:

- by exploring most combinations in ground or laboratory tests, thus reducing the number of cases for full-scale testing;
- by allowing faster testing, proceeding from one test point to the next, as long as measurements match simulation predictions;
- by increasing safety, e.g. detecting discrepancies between test results and simulation predictions, before they become incidents or accidents.

Simulation must be validated to start with, and re-checked or improved when discrepancies arise. The effort in validating simulation models is well worth the reduction in the number of full-scale test points. Also, resolving the discrepancies in simulation models can point to the solution of potential safety problems.

6.2.4. Accident-free Testing of New Systems

In the 50s and 60s, at the time of development of the Century series fighters (F-100 Super Sabre, F-101 Voodoo, F-102 Delta Dagger, F-105 Thunderchief, F-106 Delta Dart), it was not uncommon for a test programme to result in the loss of several prototypes, and some of their pilots. The development of the new generation of highly manoeuvrable fighters in the 70's (F-16 Falcon, F-18 Hornet, F-15 Eagle) proceeded with few, and in some cases, no prototypes lost. This was a direct benefit of real time simulation in support of flight testing. Another benefit is accelerated or compressed testing, covering more test cases in a given time span.

6.2.5. Ground Test Facilities

Although flight testing is the most realistic and ultimate proof of a concept, its efficiency and safety can be improved by ground testing. This may range from anechoic chambers, ranges to measure radar cross-section, or lightning strike generators, to electronics laboratories, 'iron birds' or system benches. A class of testing of increasing importance, and with rather specific requirements, is software validation and verification (V&V).

6.2.6. Testing for Reliability and Availability

The emphasis in reducing life-cycle costs increases the need for testing beyond the traditional flight and systems performance areas. Much of the testing for reliability and availability can be done on the ground, and it supplies valuable data to plan spare part inventories and prepare for operational use.

6.2.7. Maintainability and Supportability Trials

Testing for maintainability and supportability requires representative front-line personnel, so that the test engineer is relegated to the role of monitor and data collector. The test personnel must be rotated, before it becomes too skilled, and therefore unrepresentative of the average front-line support staff. This type of testing aims not only at verifying manufacturer's claims and design guarantees, but also at establishing realistic maintenance schedules and adequate support staff levels.

6.2.8. Documentation and Interoperability Aspects

The testing process also includes checking the maintenance documentation, for accuracy, clearness and comprehensiveness, as well as any other instructional tools. Interoperability testing goes one step further, i.e. assessing the feasibility of using existing support equipment with new aircraft or weapon systems.

6.2.9. Option of Autonomous Operation

On a scale of improving supportability, through increasingly autonomous operation, three levels can be discerned:

- the 'Hangar Queen', requiring specific or unique support equipment;

- the 'interoperable' aircraft, using the standard range of support trolleys;
- the 'autonomous' aircraft, dispensing the use of yellow carts, by having an internal APU (Air Power Unit), to provide self-start, or run the systems on the ground without using the main engine.

Items like an APU add to cost, and weight, take-up space, including air intakes and exhausts, and can pose integration problems, like noise and vibration interfering with the work of ground crews. Overcoming these penalties can bring a handsome reward in operability, supportability and customer satisfaction in being able to get rid of some of the flight line paraphernalia.

6.2.10. Benefits and Cost-effectiveness of Testing

Testing for the five abilities certainly increases the scope, duration and cost of a test programme. The extra cost is usually well worth the much larger savings in maintenance and support cost over the operational life of the aircraft. Similarly, reliability testing pays-off in increased operational availability, and survivability testing in reduced attrition.

6.2.11. An Overwhelming Case for Supportability

Cost and supportability have been gaining increasing importance relative to performance, in fighter design since the WWII, and tend to be ranked almost equal to performance in recent programmes. In cases of comparable performance, the cost benefits of greater supportability can prove overwhelming. An example was the decision of the US Navy to base a new derivative fighter generation F-18 E/F on the F-18 C/D Hornet rather than the F-14 A/B Tomcat. Not holding a design competition may have saved time and money, but the main motivation most probably was a clear advantage, not in performance, but in supportability:

- The F-14 is a two crew aircraft, and recruitment prospects are more consistent with the single crew F-18;
- The F-14 uses an older generation of engines and avionics leading to 35 MMHFH compared to 18 for the F-18 C/D, reduced to 12-15 for the F-18 E/F: a major reduction in shipboard spares inventory, maintenance work and support staff;
- The F-18 occupies less deck space, and has an APU dispensing with yellow carts on the deck, thus increasing the number of available aircraft and simplifying their operation.

The performance advantages of the F-14, like higher speed and longer range, were clearly not enough to call into question the supportability edge of the F-18.

6.3. Survivability of Aircraft and Crews

Cost reduction, as any worthwhile objective, has limits, e.g. it should not be pursued at the expense of excessive performance degradation or decrease in survivability. The latter can be considered in three stages: (i) preventing the aircraft from being hit in the first place (susceptibility); (ii) otherwise containing the effects of battle damage (vulnerability); (iii) when it comes to the worst, ensuring the survival and rescue of the crew. Some aspects of susceptibility were mentioned in Section 4.3.

6.3.1. Vulnerability to Anti-Aircraft Missiles

The main threats to the survivability of aircraft are missiles:

- in air combat, air-to-air missiles with high terminal agility;
- in strike missions, surface-to-air missiles with accurate guidance or large warheads. It is assumed that in attack missions, the aircraft stays out-of-range of radar-directed high rate-of-fire anti-aircraft guns.

The threat to manned aircraft is particularly acute in the case of air-to-air missiles with large off-boresight capability and extended 'no escape' envelope, and dense air defence networks with several overlapping layers of surface-to-air missile launchers and radar-directed guns.

6.3.2. Expendable and Towed Decoys

Besides electronic countermeasures against radar-guided missiles, the main current form of defence is the use of expendable or towed decoys, to deceive the guidance systems, viz. IR flares and radar chaff or reflectors. Missile guidance systems are becoming increasingly sophisticated in discriminating the target from decoys.

6.3.3. Multi-Spectral, Multi-Mode and Imaging Seekers

Even small shoulder-fired surface-to-air missiles now employ multi-spectral Infra-red seekers, so that effective decoys need to operate in several spectral bands. Larger surface-to-air and air-to-air missiles employ dual mode or twin infra-red and radar seekers, so that the IR flares and radar chaff need to be co-located to act effectively as decoys. Imaging seekers are even more sophisticated in distinguishing aircraft silhouettes from decoy clouds or towed decoys.

6.3.4. Active Self-Defence Systems

As electronic countermeasures and passive towed decoys reach the limits of their effectiveness, consideration must be given to active self-defensive systems. If or when the latter in turn become ineffective, the manned combat aircraft must give way to the UAV or UTA. Thus active defensive systems may be the last life extender of the manned aircraft. Among the possible principles of operation of active short-range defensive systems for aircraft, at least two should be mentioned: low-power lasers and short-range rockets, both cued by threat warning receivers (TWRs).

6.3.5. Self-Defence by Short-Range Rockets

The use of short-range rockets, e.g. of 3 to 5 inch calibre, for self-defence, may arise sooner for battle tanks than for aircraft. The advent of top-attack anti-tank missiles and sub-munitions, has made it impossible to protect the whole topside of the tank with armour. The self-defence rockets need to destroy incoming missiles at sufficient distance for the detonation of their warheads to be harmless; this distance is greater for a soft-skinned aircraft than for a well armoured battle tank, but tens of meters is enough in most cases. Thus the rocket may need no more than timely cueing from a radar warning receiver (RWR) and firing in the approximate direction of the incoming missile, for a proximity-fused warhead to destroy it or guidance during flight may needed. The rockets/missiles could be housed in containers resembling either rocket pods or decoy ejectors.

6.3.6. Low-Power Lasers for Self-Defence

For short-range defence against incoming missiles, a low-power laser may be sufficient, since atmospheric absorption is not a problem and burn-through high-energy densities are not needed. A short-range low-power laser could blind the IR seekers, and damage the dielectric radomes of radar seekers, of incoming missiles, at a few hundred metres, causing them to miss the target. Again, accurate cueing information from a threat warning receiver (TWR), and quick steering of the laser beam are essential. The TWR could be a RWR for radar guided missile, or an UV (ultraviolet) or IR (infrared) sensor for IR-guided missiles. The UV-receiver is preferable at low altitudes, because it is less susceptible to false alarms from warm objects in the landscape than an IR-detector; the latter could have increased range at high-altitudes.

6.3.7. Surviving a Shell Hit or Splinters

The chances of an aircraft surviving a few cannon shell hits or some fragmentation warhead splinters, and at least returning safely to base, are improved by:

- having redundant, well-separated systems, like control runs;
- having reconfigurable systems, able to identify and isolate failures;
- using fail-safe and multi-path structures, which resist partial damage;
- protecting fuel tanks and weapons bays against fires and explosions;
- having means to extinguish engine bay fires and contain turbine debris;
- using lightweight armour around the cockpit and critical systems, to the extent practicable.

6.3.8. Helicopter and Airplane Survivability

The hit survivability tends to be greater for helicopters, e.g. they may have composite blades able to take several shell punctures without separating from the rotor hub. The helicopter can also be made crash resistant, allowing survival after an emergency landing using auto-rotation. Being soft-skinned vehicles, helicopters or airplanes are unlikely to survive a prolonged shell burst, explosive shells or the nearby blast of a sizeable warhead.

6.3.9. Ejection Seat Improvements

If it comes to the worst, the crew should be able to eject safely from almost any flight condition. In the West, the zero-zero ejection seat, assuring safe escape at low speed and altitude, has become almost standard. It has been assumed that ejection at high-speed, or from unusual aircraft attitudes, will carry an extra risk of injury, but may still be survivable. In this respect, the West which prides itself in the respect for human rights, has been outdone by developments in the former Soviet Union. Russian ejection seats improve on ejection capability of Western seats, in at least three respects:

- having aircraft attitude sensors, allowing safe ejection from unusual attitudes;
- deploying a wind blast deflector, to project the face during high-speed ejections;
- providing improved limb restraints, to reduce the risk of injury during ejection.

The first feature was dramatically demonstrated after a mid-air collision of two Mig-29s during a display at the 1993 Farnborough Air Show. It is not known whether the Russian ejection seats match the capability of Western seats at the low speed and altitude end of the flight envelope. In any case, it is clear that it should be technically feasible to bring significant improvements to the high-speed ejection capability of Western seats.

6.3.10. Recovery of Downed Aircrew

A safe ejection may not be the end of the story for an aircrew over enemy territory. Some rogue regimes and violent factions use the media to display their disrespect for the rights of prisoners under the Geneva convention. Trying to rescue an aircrew downed over enemy territory can be an even more hazardous mission than SEAD. The rescue attempt may become a calculated trap, and the use of air defence, ground attack and command and control assets in addition to fire suppression aircraft and rescue helicopters, may fail to prevent further casualties. Thus consideration should be given to providing for more than just safe ejection. A distress beacon, with GPS receiver, could signal position for rapid rescue, hopefully ahead of the enemy. Better still, the possibility of providing the pilot with some means to fly away some distance or loiter for some time, awaiting rescue, should be considered. One possibility would be a fold-away autogiro, with simple rotor-tip ramjet propulsion.

6.4. Upgraded vs. All-New Aircraft

Upgrades to existing aircraft are a cost-effective way to extend the operational life of existing fleets, or to close a window of vulnerability, until new types can be developed or afforded. A less advisable form of false economy is the continued operation and upgrade of outdated aircraft, with high support costs, simply because of a shortage of funds to replace them with newer types, which are more effective and have lower life-cycle costs. The range of aircraft upgrades can go almost as far as an all-new design, and the usual 'menu' by order of priority is: new weapons, improved defensive systems, updated avionics, structural life extension, cockpit modernisation, more reliable systems, and more advanced engines.

6.4.1. Fitting New Weapons

An air force procuring a new aircraft may wish to use with it, its current inventory of air-to-air and air-to-ground weapons, some of which may not have been previously qualified on that aircraft. During the operational life of the aircraft, new weapons may become available, which may enhance its effectiveness, allow the performance of additional missions or improve self-defence. All of these are motivations for fitting new weapons. The qualification of an existing aircraft to carry new weapons, will involve at least demonstration of safe release and separation, e.g. in the case of bombs. In the case of missiles or gun pods, additional trials may be needed. In all cases, structural loads, asymmetric configurations, ground and undercarriage clearance, pylons, attachment points and ejectors, mechanical and/or electrical connections and like matters need to be considered.

6.4.2. The Need for Upgraded Avionics

The effective use of new weapons may require upgraded avionics, e.g.:

- effective use of several BVR fire-and-forget air-to-air missiles will require an intercept radar able to track several targets simultaneously;
- launch of air-to-surface missiles against well-defined targets may require cueing information from on-board sensors.

In other cases, the fast pace of progress in electronics and computing, may motivate the replacement of older avionics, or allow the installation of new systems, e.g. sensors, navigation, etc.

6.4.3. Improved Defensive Systems

During the operational life of an aircraft, the threat may evolve, or new and better equipped potential adversaries may emerge. The survivability of the existing fleet, the expected rates of attrition and the ability to accomplish essential missions, may degrade as a consequence. In such conditions, improving electronics countermeasures like jamming, adding radar warning receivers or other electronic support measures, and fitting more effective expendable or towed decoys, may receive high priority. The choice between permanent internal installation and procurement of external pods is not always easy. The latter is less expensive, but may involve loss of flight performance and reduction in the number of pylons available for weapons; it is the preferred choice in low threat environments. In high threat scenarios, the added expense of internal installation may be justified, to avoid a systematic loss of flight performance and weapons loads and flexibility.

6.4.4. Updated Cockpit and Displays

The effective use of new weapons, defensive systems and avionics, may require changes to the cockpit. Cockpit changes may be justified on their own, e.g. fitting a head-up display, (HUD) or changing to one with a wider field-of-view. Fitting multi-function (MFD) displays, either Liquid Crystal displays (LCD) or cathode ray tubes (CRT), may reduce crew workload and improve situational awareness. Having to update some of the cockpit systems for one reason or another, may become the pretext for changing to a modern digital cockpit altogether, possibly including controls, e.g. hands on throttle and stick (HOTAS).

6.4.5. Cost of Mission Systems

Mission systems and avionics may account for about one-third of the acquisition cost of a new aircraft. As they tend to be upgraded more often than the airframe, viz. once or twice over the operational life of an aircraft, they tend to have an even greater preponderance in upgrade costs, such as a mid-life update (MLU). The cost of a MLU can be a significant fraction of original acquisition cost, unless some restraint is exercised in the variety and specifications of mission systems. On the other hand, given the investment in mission systems, the operator may consider the wisdom of some airframe upgrades as well, while still stopping short of an extensive modification, approaching the cost but not the effectiveness, of an all-new aircraft.

6.4.6. Structural Life Extension

Having invested heavily in new mission systems, it is appropriate to ensure that more flight hours can be put on the airframe. This is usually the aim of a structural life extension programme. Airframe life is consumed disproportionately by manoeuvres involving high g-loads. If the airframe has not been subjected to frequent high g-loads, little structural refurbishment is needed. More structural work will be needed in the case of frequent high g-loads (e.g. air superiority or attack aircraft), repeated impulsive loads (e.g. unflared carrier landings) operation in corrosive environments (e.g. salt water spray on amphibians or maritime patrol aircraft), flight in turbulence (low-level penetration or interdiction), or repeated in-flight refuelling (tanker aircraft). Even in such cases, an airframe life extension may be well worth the thousands of extra flying hours or additional years of operation it affords.

6.4.7. Fitting more Modern Engines

More modern engines can offer significant improvements in thrust-to-weight and thrust-to-volume ratio and reductions in specific fuel consumption (SFC). Fitting a smaller engine with the same thrust is usually not a good choice, since it requires more structural changes in the engine bay area, possibly re-balancing the aircraft with forward ballast, etc. Fitting an engine of similar size and weight is simpler, and has the benefit of higher thrust, possibly still with comparable or reduced total fuel consumption, due to the lower SFC. The extra thrust may have limited benefit as concerns flight performance, since the aerodynamics of the aircraft is unchanged. The main benefit would be an increase in payload-range, weapon or fuel load, and endurance, consistent with a higher gross weight, which may also require structural changes. Unfortunately, the cost of modern jet engines tends to be rather high, making a multi-million dollar change of engine less attractive, unless the replacement of the old engine is almost mandatory, due to spare part or reliability problems.

6.4.8. Re-Engining Tanker Aircraft

A case of almost compelling engine change is the replacement of Pratt & Whitney JT3C turbojets by CFM 56 turbofans in the Boeing KC-135 Stratotanker aircraft, which triples the fuel load delivered at a given range, because the new engines have a:

- higher thrust, allowing a significant gross weight increase, and doubling of the fuel load;
- lower fuel consumption, so that the tanker consumes less fuel itself.

In this case, in spite of the high cost (of the order of ten million dollars) of fitting four new engines, the operational benefits are overwhelming. Other benefits include lower noise and emissions.

6.5. Force Mix

The optimum force mix should use the minimum number of aircraft types, to reduce logistics costs and maximise interoperability. Also, the development and production of new aircraft should be phased within a smooth budget, without leaving windows of vulnerability to the threat. Both objectives, viz. minimising different aircraft types and balancing the defence budget, concern the effective performance of the full range of operational missions, for fighters, support aircraft, helicopters and more specialised types (e.g. maritime patrol).

6.5.1. Missions for Fighter Types

Fighter type aircraft could perform six missions:

- air superiority and combat air patrol (e.g. F-15, Su-27);
- long-range interception (F-14, Tornado ADV);
- ground attack (e.g. F-16);
- long-range interdiction (e.g. Tornado IDS);
- electronic support measures and reconnaissance (e.g. Tornado ECR);
- suppression of enemy air defences (e.g. F-4G).

6.5.2. High and Low-Force Mix

An air force with a high- (F-15, Su-27) /low- (F-16, Mig-29) force mix could perform the six fighter type missions with variants of just two types:

- a single-seat lightweight fighter for air superiority and ground attack;
- a two-seat long-range fighter for interception, interdiction, SEAD and ESM.

A single-seat version of the heavy fighter could also be used for air superiority. Some missions may be shifted to UAVs.

6.5.3. Partial Replacement of Forces

Most European air forces cannot afford the high/low force mix, with the possible exception of Britain, Germany, Italy and France, and have only the low end, e.g. F-16. In both cases, replacement of the whole fighter force, for each new generation, as in the United States and Russia (the latter perhaps no more), is not feasible. The European defence budgets will accommodate only replacing about one-half the fighter force at each generation, and keeping the other half of the preceding generation with upgrades. Some missions will still require significant aircraft modifications, e.g. STOVL for amphibious operations or operation from through-deck cruisers, and high-sink rate undercarriage (24ft/s instead of 12ft/sec land-based) and strengthened structure for carrier borne aircraft, which have to cope with a pitching-up deck rather than a fixed runway.

6.5.4. Tankers, AWACS and J-STARS

A single transport type, e.g. a civil jet airliner derivative, could perform three missions:

- in-flight refuelling tanker, combined with personnel or cargo transport;
- AWACS (airborne warning and control system) type;
- STARS (surveillance, target acquisition, reconnaissance and tracking).

The latter two missions require extensive avionics suites; they could conceivably be combined in a larger aircraft, but the implications on vulnerability, redundancy and cost should be assessed.

6.5.5. Tactical Transport Derivatives

A tactical turboprop transport like the European FLA (Future Large Aircraft) would be an alternative for a tanker aircraft, and perhaps also for the AWACS and STARS mission.

6.5.6. Strategic Transport and Command

A large strategic transport, like the C-5 or C-17, is a separate type, with an airborne command aircraft, like the Boeing E-4, as derivative: an airliner conversion (the Boeing 747 in the case of the E-4) is an obvious alternative.

6.5.7. Long-Range Maritime Patrol

A tactical transport airframe like FLA may be too large for long-range maritime patrol and anti-submarine warfare, but it might be preferable to a regional turboprop airframe which is too small, or continuing to use an old airframe (like the P-3 Orion), or developing a new one (too costly).

6.5.8. Helicopter Types and Roles

The combat and anti-tank helicopter stands alone, whereas the light helicopter can perform several missions:

- armed scout;
- casualty evacuation;
- observation;
- liaison.

6.5.9. Medium Helicopter or Convertible

The remaining helicopter missions would fall to a medium type, or a convertible:

- troop transport;
- search and rescue;
- battlefield surveillance;
- anti-submarine warfare and other naval roles (mid-course guidance for ship-to-ship missiles, airborne early warning, ship on board delivery, search and rescue).

6.5.10. Regional Turboprop

A regional turboprop airframe could do battlefield surveillance, logistic support, and coastal surveillance.

6.5.11. Assignment of Types and Missions

The preceding outline of missions attempts to minimise the number of dedicated military developments, and make the best use of civil derivatives. The use of UAV/UTA/UCAVs for RSTA, strike, SEAD and/or ESM would be a major innovation.

7. RECOMENDATIONS AND PROSPECTS

The main purpose of the present report has been to review the technologies with greater potential to improve combat aircraft capability and affordability in the 2020 timeframe. In this concluding section some of the consequences are highlighted, in three areas:

- an ensemble of advanced technologies which, together, would justify the development of a new combat aircraft family;
- a re-organisation of the industrial base able to support competitive development with declining defence budgets and fewer aircraft procurement programmes;
- a set of long-term research objectives aimed at keeping air power as a viable asset well into the next century.

7.1. An Advanced 20-ton Thrust Engine

A new generation of combat aircraft which we term NGF (New Generation Fighter) could be designed around an advanced 20-ton thrust class (or two 10-ton thrust class) engine(s), weighing little more than 1 ton, and no larger in overall dimensions, or cross-sectional area, than current fighter engines. The new engine would have a military (i.e. non-afterburning) thrust of at least 12 ton, allowing supersonic cruise, with a total fuel consumption comparable to current engines, due to a lower specific fuel consumption. It should be fitted with a two-axis thrust vectoring nozzle, for post-stall flight and control and stabilisation across the flight envelope, plus the option of vertically deflected thrust for STOVL. Together with these enhancements, part count, maintenance requirements, durability and cost should also improve, or at least not degrade. The attractions of a twin-engine solution remain, e.g. for carrier-borne operations, or use over water or in arctic regions, even if two engines may cost more than a single larger one.

The question of one versus two engines, like that of one versus two crew, is as old as fighter design, and involves a share of tradition and operational philosophy. The USN has traditionally required twin-engine fighters for most missions (F-4, F-14, F-18, and A-6), although it has operated single-engine types (F-8, A-4 and A-7) with comparable reliability. The RAF has had a consistent preference for twin engines (Meteor, Javelin, Lightning, Jaguar, Tornado, EF 2000), whereas the USAF has fielded simultaneously one (F-104, F-105, F-106) and twin-engine (F-101, F-4) fighters, of comparable or dissimilar (one engine F-16 or twin-engine F-15) capabilities. The French Armée de l'Air has favoured in the past twin-engine prototype fighters, but had to bow to the political choice of cheaper, more exportable single engine types (Mirage III, F1, 2000), until the advent of Rafale. Advances in engine technology and cost limits may favour the single engine solution, but they may not close the debate.

7.2. Reducing the Crew Complement

It is well accepted that the air combat mission can be performed by a single-seat aircraft (F-15C, Su-27, Rafale, F-22, EF 2000), although there also examples of two-seaters (F-4, F-14, Tornado ADV), unlikely to be repeated in the future. In contrast, long-range interdiction has usually been performed by two-seaters (F-111, Tornado IDS, Su-24 Fencer, Su-32 Flanker, F-15E, Mirage 2000N, attack version of Rafale). It is admitted that pilot workload in an all-weather attack mission on an F-16C is close to the acceptable limit. On the other hand, an F-117 flies a mostly automated mission, with the pilot acting mainly as systems supervisor, who gives consent to the weapons release. A single-seat attack aircraft becomes feasible, if the task of flying the aircraft is automated, which may in fact be needed to show the smallest RCS (radar cross-section) to the known threats. For other missions, like SEAD (suppression of enemy air defences), the replacement of the two-seat F-4G Wild Weasel by the single-seat F-16 with automatic threat assessment and response systems, has been somewhat controversial. Concerning electronic countermeasures, it has been performed by two-seaters (EF-111, Tornado ECR) or even four-seaters (EA-6B), and the USN plans for a replacement of the latter are based on a two-seat F-18. Thus the choice of one or two-seat fighters, for the most demanding and complex missions, depends on the philosophy and traditions of the operator and the extent to which automation provides a satisfactory or desirable alternative to a second crew member. In the present work, the conservative approach, of presenting as two-seat fighters, those intended for missions for which the single-seater solution is not a subject of consensus, is followed.

It should be kept in mind that the measurement of workload is still incipient, and it is hard to prove that a single crew cannot do the job, or that two crew are needed. Pilots are very good at using past experience, and shedding away unneeded tasks. It may be that most of the mission can be performed by a single crew, or even by automation, but at critical times the second crew member is a definite asset. Most aircraft are lost without the crew knowing what hit them, perhaps because the single crew was concentrating on a task, like attack or intercept, and overlooked its own defence. Another pair of eyes, or even more, another mind, may improve mission performance, or gain a precious warning. The old division of tasks, where one attacks and the other looks out for the threat may still apply. All this has to be weighted against the penalties of two crew, in terms of aircraft size and cost, and crew recruitment and training. In the case of the Comanche helicopter, and also the Ka-50, the single crew concept was discarded for a two-crew one. Nap-of-the-earth (NOE) flying plus anti-tank/helicopter combat was considered by pilots to be too high a workload for a single crew.

7.3. Modular Multi-Mission Airframe

Around this advanced engine would be built a modular airframe, able to perform nearly all seven of the fighter missions:

(i) a single-seat specialised STOVL variant, with a lift system in the fuselage behind the cockpit;

(ii) a single-seat CTOL variant for ground attack, using this space for increased internal fuel tankage or additional internal weapons bays;

(iii) a single-seat CTOL variant aimed at air superiority, with improved stealthiness, in aspects other than head-on, e.g. smoother structural joints and more radar absorbent material;

(iv) a two-seat interdiction variant, with the second crew member taking some of the space of the lift system, and other changes to increase payload-range over and above that of variant ii;

(v) a possible two-seat long-range interceptor, combining the extra crew member and range of variant iv with improved stealthiness of variant iii;

(vi) a specialised electronic support measures (ESM) variant, based on the two-seat interdiction variant, with a comprehensive avionics suite, allowing also surveillance and reconnaissance;

(vii) a specialised suppression of enemy air defence (SEAD) version, combining the two-seat avionics intensive variant vi, with improved stealthiness of variant v, and armament options from variant iv, with additional anti-radiation missile capability.

7.4. Low and High Family Mix

It is clear that the last four variants would need to be heavier and more capable aircraft. This could still be accommodated within the same family, by means of a number of optional changes:

- availability of a growth engine, with a thrust of around 25 ton, to power later variants, enabling a higher gross weight;
- development of a range of conformal packs, to increase fuel load or accommodate additional weapons, taking advantage of the higher gross weights, with little drag penalty;
- possible development of a variable-geometry wing, to increase range and endurance to values similar to those of the F-111.

7.5. Keeping within a Cost Target

The cost target should be 40 million US dollars for the simplest variant ii, up to, but not exceeding, 60 million dollars for variants i, iv and v. The cost of variants vi and vii would be strongly dependent on avionics fit, but could be reduced by retaining systems from existing aircraft, in cases where they still have adequate performance.

7.6. Choice of Mission Systems

Keeping within this cost target will require considerable discipline in choosing mission systems, to retain the essential advanced features and avoid costly over-specification without supporting synergies. The essential mission systems would include:

- a multi-mode, phased array radar (perhaps with several conformal antennas), including pulse Doppler track-while-scan of multiple targets for air combat, synthetic aperture mode for ground target imaging and identification, with simultaneous terrain avoidance and navigation capability, and clutter rejection and ECCM features, plus possibly a spread spectrum, low-power low-probability of intercept mode;
- a passive infra-red search and track (IRST) system allowing target engagement at intermediate ranges without use of active radar modes;
- a navigation system combining mainly three systems: GPS with integrity monitoring, using more than four satellites when the latter are visible; inertial navigation system (INS) based on a ring-laser platform; terrain comparison (TERCOM) with radio or radar altimeter input minimising changes of enemy detection;
- an internal, upgradeable defensive system, including threat warning and assessment, jamming modes, and expendable and towed decoys, and provision for active defence;
- a high-capability, secure, jam-proof data link to other tactical and support aircraft, together with the capability to fuse data with that generated by the aircraft on-board sensors.

This avionics suite would not be cheap, so that any other necessary systems should be low cost, either by using existing off-the-shelf components, or incorporating commercial technologies; the aim should be to satisfy the need at minimum cost, rather than approach the state-of-the-art. This could apply to computing, displays (HUD, HDD, CRT or LLD types), controls, communications, life support, and various other systems. Particular care should be taken to specify an open, upgradeable architecture, to try to use existing, proven software; as far as possible, software should be hardware independent.

7.7. Incorporation of Stealthy Features

Due to the high cost and lifetime penalties of extreme stealth, the cost target cannot be met without some restraint in this area too. First, the systems architecture and data links should exploit to the maximum extent mission planning and cooperation with other friendly forces to maximise situational awareness and increase survivability. Stealth features should be compatible with a large internal volume, for fuel and weapons; this could be a key driver in the selection of a configuration. Stealth might be degraded in the basic version by doing without very close tolerances and part fit. Limiting stealth to the frontal arc (±30° say), will allow a considerable economy, and may be acceptable for a strike aircraft, though less so for an air-superiority fighter. A fraction of the cost of stealth might be better spent in miniaturising air-to-air and air-to-surface weapons, to allow stealthy carriage of larger numbers in internal bays and conformal packs. The general perspective would be to exploit stealth as an enhancement of mission effectiveness and survivability, but not at an extremely high cost, or underestimating that the value of stealth may be reduced by improved sensors such as long wave and bi-static radars. Attention to other observables, like IR signature, noise, camouflage and contrails must complement radar stealth.

7.8. American and European Programs

The preceding description might be taken as a description of the JAST (Joint Advanced Strike Technology) JSF (Joint Strike Fighter) program suitably expanded to include every other fighter role, including air superiority. The latter variant might not achieve the F-22 levels of stealth, but a moderate degradation there could be worth the reduced cost and the benefits of interoperability. When making comparisons of aircraft in full-scale development and paper projects, particularly in cost areas, some care is needed not to let optimism be disproved by later experience of cost growth, of what appeared to be at first the low-cost panacea.

On the European side of the Atlantic, the fighter programme outlined could be a follow-on to the costly duplication and waste of resources in developing Rafale and EFA with comparable technologies but distinct implementations of airframes, engines and systems. Its production base could be broadened beyond the larger states (France, Great Britain, Germany, Italy and Spain), to satisfy the needs of smaller or less wealthy states (Sweden, Netherlands, Belgium, Denmark, Norway, Greece, Portugal, Turkey, and perhaps also Eastern Europe) at the low end of the family. The larger states might also benefit from complementing small numbers of the more costly high-capability variants, with larger numbers of the cheaper low-end versions, with logistics and interoperability benefits.

Transatlantic cooperation remains possible, without surrender of design capability, or relegation to sub-contractor or licence production status. The STOVL variant i could be subject to joint development, following the Harrier/AV-8 tradition. The very specialised variants vi and vii, needed in small numbers, but still essential for tactical missions, could be split, e.g. SEAD for the U.S.A. and ESM for Europe. The variants ii, iii, iv and v needed in larger numbers, would justify an element of competition, and face a potential enemy with more than one type of weapon system.

7.9. Show Stoppers and Detractors

Whereas a program like JAST/JSF in the US is bound to be successful if it meets its technical and cost targets, the politics of cooperation in Europe are complicated by nationalism in various guises, from protection of key industrial sectors, to retention of separate final assembly lines. Economic pressures may force the kind of compromises that industrial consortia like Airbus, and Air Staffs in cooperative programmes have become experienced in.

There may be, in addition, technical issues, like flight control software problems, causing programme delays and cost overruns, to detract from the already less than enthusiastic public and political support for large defence programmes. The aerospace community can hardly afford protracted technical problems or lax programme management, without putting its future at risk. Even if large aircraft programmes have no satisfactory local alternative, upgrades to existing fleets, imports of other aircraft, and production cutbacks can be nearly as damaging in the long-term as cancellations.

7.10. Reducing Numbers of Aircraft Types

The example of Grumann's announcement that it was giving up aircraft design (before its acquisition by Northrop), after several decades of activity in this area, shows that a manufacturer cannot survive any longer producing aeroplanes for one armed service of the West's most powerful nation.

The reduction in the number of aircraft types, applies to all air forces, and is well illustrated by the past and likely future of the Carrier Air Wing (CAW). About 10 years ago a CAW consisted of:

- 2 air defence squadrons, with 14 F-14 Tomcats or F-18 Hornets,
- 1 light attack squadron with 12 A-7 Corsairs,
- 2 heavy attack squadrons with 12 A-6 Intruders,
- 1 ASW squadron with 8-10 S-3 Vikings,
- 1 EW flight with 4 EA-6 Intruders,
- 1 AEW flight with 4 E-2 Hawkeyes,
- 1 reconnaissance flight with 4 RA-5 Vigilante,
- 1 tanker flight with KA-6 Intruders,
- 1 COD (Carrier On-board Delivery) flight with C-2 Transports,
- 1 helicopter flight.

In all 80-100 aircraft, in 6 squadrons and 6 flights, with 9 aircraft types, not counting variants.

With current aircraft development costs and life-cycles, what can be expected in the future is perhaps just two types:

- one combat type, the F-18E/F will have to perform all intercept, attack and reconnaissance missions, including EW, probably complemented by JSF;
- one utility type (helicopter or convertible) should have to perform all other roles, including AEW, ASW, tank and transport.

7.11. A Modular UAV Family

The single family of new generation fighters (NGF) would be complemented by modular UAV family (MUF). The latter would be autonomous vehicles, about half the size of the NGF, with choice of:

- payload, e.g. sensors, warhead or both, in the 2000-4000 lb class;
- wing, e.g. large span for high-attitude long-endurance RSTA, or short span for low-altitude strike, ESM and SEAD;
- engine, e.g. turbojet or turbofan, depending on speed/altitude operating regime.

7.12. A Triple Force Mix

The combat force mix in the coming two or three decades could consist of three elements:

- the existing aircraft with upgrades, which, due to their lack of stealth, would operate at larger stand-off distances, in safe air space;
- the NGF which would perform the more demanding missions, involving penetration of hostile airspace;
- the UTAs which would perform simple but high-risk missions for which no manned aircraft should be exposed.

This triple force mix could cope with a variety of situations:

- against a well equipped opponent, the NGF would have the superiority to spearhead an attack, and sustain throughout the conflict the more demanding missions;
- the large fleet of upgraded fighters would provide the numbers to cope with a larger regional conflict, e.g. invasion of one country by another;
- the UTAs would take small scale high-risk missions, where loss of crew or positive identification must be excluded.

The force mix would evolve depending on:

- technology maturation, which would shift more missions to UTAs;
- availability of resources, which would allow more new NGFs to replace upgraded fighters;
- perception of the threat, which would allow reduction of the fleet, by retiring older fighters.

7.13. Keeping Alive Design Terms

The recent consolidation in the aerospace industry, with the formation of Lockheed-Martin, Northrop-Grumman, and Boeing-Rockwell, may not be enough to compensate for the smaller number of aircraft programmes of increasing size. With fewer aircraft programmes, and bigger gaps in between, it is not obvious that existing design teams can be maintained. Going to 1-3 new major combat aircraft per decade, how can the 4 to 6 remaining design teams on each side of the Atlantic be kept alive?

The answer is that if only winning teams have work, few will survive, and the element of competition will be degraded. The alternative is to have deliberate programmes aiming to keep alive design expertise, in the form of technology demonstrators.

These technology demonstrators would be turned to production programmes when:

- they had achieved a significant increase in capability over aircraft in service;
- the service aircraft need replacement;
- the budget would accommodate a production programme.

A sustained programme of technology demonstrators to keep at least 2-4 design teams active would not be cheap, but will cost far less than losing the choice and quality of competition. Also the teams could be kept active and useful by competing on design of upgrades for the existing fleets, or proving out new missions for UTAs.

7.14. Preserving the Industrial Base

It is clear that the present production capability is higher than future needs, and it will have to be downsized. The question is how?

The traditional method of "winner takes all" was once good but no longer. Winner takes all is good: (i) to promote competition and select the best, if (ii) there are several other programmes to give a chance to the losers. In this way, only the consistent loser disappears, at no loss to anyone.

In the present conditions, a team which loses one or two competitions will not have another chance in ten years: it will disappear. The next competitions will decide very few survivors, and the excessive selection can lead to almost monopoly.

The alternative, is to make the winner share the contract with the 'able' losers, albeit with a larger share as reward. In this way, production would be spread over 3 to 6 major contractors, which would be able to re-compete the next time around, even if that was 5 or 10 years later.

7.15. Conditioning the Free Enterprise

All this may look as a deviation from free enterprise. It is in fact a modification of the old Soviet System: design bureaus compete, and production is carried out in the same factories. But there is a crucial difference, in the winner having a bigger share, and production being also competitive. Also the Soviet Military complex did function in a capitalist frame, with competition and material incentives.

The aviation sector has shown how quickly 'socialism' can enter the 'capitalist' world: several US airlines are now partly owned by their employees. In the military field, it is in no one's interest to let what remains of a competitive design and production capability be wiped out by the winner taking all of a few contracts with gaps of many years in between.

In conclusion, the alternative is:

- several design teams are kept active with technology demonstrator programmes;
- when a production programme emerges, it is shared between the winner and 'able' losers.

This approach can avoid massive funding of the winner, and elimination of its competitors in future contracts.

7.16. The New Development/Deployment Cycle

The preceding considerations on preserving competitive development and production, by keeping alive design teams and maintaining the industrial base, can be summarised in the following aircraft development/deployment cycle:

- design competitions are held regularly, e.g. every few years; every capable submission is fully funded, winner or exceptional entries are rewarded, promising new teams receive incentives - the cost of doing so is low;
- particularly innovative and progressive designs may lead to demonstrator programmes, keeping the basic set of test facilities in use for research, not just development of variants of existing aircraft;
- when sufficient technology advances have been demonstrated, to warrant a new aircraft programme and motivate the corresponding allocation of funds, a more formal competition is held;
- the winner shares production with the able losers, while retaining a larger share as incentive.

7.17. Broad vs. Directed Research

Continuing progress in air power will require the pursuit of basic research in the full spectrum of technologies; this is not a costly activity, and should not be the target of short-sighted economies, which would stifle the source of new ideas for future developments. When it comes to large-scale demonstrations or full-scale developments, greater selectiveness is essential, to profit from dual-use technologies and target scarce resources for maximum effect. The usual controversy between broad vs. directed research is resolved by distinguishing two classes: basic research must be broad, applied research should be directed.

7.18. Future Development Activities

The following list does not attempt to be exhaustive in any way, or to set any particular priorities. It is merely a reminder of some aspects, which might be overlooked otherwise:

- providing means for a downed aircrew to move away, or loiter, while awaiting for a speedy rescue;
- development of improved ejection seats, for better protection of the pilot at high-speed or in extreme aircraft attitudes;
- demonstrating aircraft self-defence systems based on short-range rockets, low power lasers, or other concepts;
- researching the factors limiting the possibility of a remote crew of a UAV to have the same situational awareness and control options as the on-board crew of a manned aircraft;
- improving the knowledge of human factors relating to training and mission performance;
- rationalisation, up-dating and replacement of test facilities;
- effective internetting of test ranges;
- getting to the roots of the current flight control problems, like PIOs;
- keeping down engine costs, while preserving capability advances;
- devising cost-saving open, reconfigurable avionics architectures allowing easy replacement of hardware units;
- improving software validation and verification, and developing open software architectures which are hardware independent;
- identifying stealthy configurations with large internal volume;
- miniaturising air-to-air and air-to-surface weapons for stealthy carriage in larger numbers;
- designing aircraft configurations compatible with a wide range of conformal fuel and weapon carriage;
- designing mission systems to take most advantage of mission planning;
- providing effective, real time data sharing between platforms;
- improving sensor fusion and target identification and tracking algorithms;
- providing covert surveillance and target tracking systems;
- implementing distributed, conformal radar systems;
- integrating reliable and accurate navigation systems;
- adapting commercial computers or chips to airborne needs;
- devising strategies for joint operation of manned and unmanned aircraft;
- making a technology road map to afford timely and at-low-risk upgrades to existing systems and new designs;
- preparing staffs at all levels, from commanders through pilots to maintenance personnel, for new technologies and concepts of operation;
- sharing of resources and capabilities in the Alliance in an optimum way.

Most of the preceding objectives are ‘straightforward’ technological challenges, but the last four involve other aspects.

8. CONCLUSION

The preceding review has covered modern aircraft design practices aimed at arriving at a reasonable set of compromises between the usual set of 'abilities', in approximate order of priority: capability, affordability, survivability, availability and reliability, maintainability, supportability and interoperability. This account of enabling aerospace technologies points both to near-term alternatives available to air forces and the longer term trends in their mission and equipment.

8.1. Near-Term Alternatives

From the point-of-view of planning the evolution of an Air Force inventory, the preceding account of enabling technologies, leaves three alternatives, namely; upgrading the aircraft in service, acquiring new manned aircraft, or shifting some of the missions to remotely manned vehicles.

8.1.1. System Improvements

The high cost of development and acquisition of new fighters, and declining defence budgets, make the upgrading of existing fleets the preferred option, as long as this provides a credible operational capability. Combat effectiveness will require the introduction of new weapons as the first priority. For air-to-air combat:

- a short-range AAM (air-to-air missile) with high off-boresight ability;
- a fire-and-forget BVR (Beyond Visual Range) AAM with good terminal manoeuvrability.

For air-to-ground missions:

- 'smart' glide bombs, allowing precision strike from stand-off distances out of reach of the short-range air defences;
- air-to-surface missiles with ranges up to tens of kilometres, out-of-reach of medium-range air defences;
- long-range munitions dispensers launched hundreds of kilometres from the target, out of range of almost all surface-to-air missile systems.

It will be increasingly necessary to allow for the carriage, on strike missions, of air-to-air missiles for self-defence, and anti-radiation missiles for defence suppression. The need for defensive measures will increase: more comprehensive electronic countermeasures, a larger complement of flares and chaff cartridges, more sophisticated towed and air-launched decoys and, eventually, active self-defence systems using lasers or short-range rockets. The new weapons and defensive systems, will require upgrades in sensors, and other systems. The critical question is: what is the limit to such upgrades? It may not be aircraft performance by itself, but rather survivability in the face of ever more sophisticated threats.

8.1.2. The Limits of Stealth

The next two decades will see an increasing use of stealth fighters by the United States. The effect on air combat of the F-22 may be as great as the success of the F-117 in the Gulf War. Once stealth fighters are deployed in some numbers, there will be increased emphasis in the development of anti-stealth sensors, like bi-static radars, long wavelength radars, more sensitive infra-red detectors, etc. The race between stealth and counter-stealth may not be won by either side, but each advance will make more critical the situation of the one sure loser: the conventional non-stealthy aircraft. It will become a larger, and more difficult to conceal, target, as sensors advance to counter stealth. Besides, high-agility air-to-air missiles, and more sophisticated surface-to-air missiles, will make the conventional aircraft more vulnerable, if its 'signature' cannot be substantially reduced. Although 'stealthiness' of a conventional aircraft can be improved, only a totally new design will provide a substantial degree of 'signature' reduction. If stealth becomes essential to survivability, then existing fighter fleets will tend to be limited to stand-off weapon launchers, or operation in 'low-threat' environments; whether the 'low-threat' environment will exist in the future, is open to debate, for even the shoulder-fired surface-to-air missiles may be expected to become more sophisticated and difficult to decoy, and more advanced weapons will continue to proliferate.

8.1.3. The Unmanned Tactical Aircraft

As existing conventional aircraft become more vulnerable, the only alternative to a new and expensive stealth fighter, becomes the Unmanned Air Vehicle (UAV). The UAV could be much smaller and survivable than a manned aircraft, and incorporate stealth technologies at a lower cost, if automation, miniaturisation and data exchange progress sufficiently to make the remote pilot as effective as a pilot on board. These are big 'ifs' which are likely to be met in the next two decades, only for the simpler missions, like reconnaissance or attack of well-defined targets. Highly dynamic missions, like air combat, are difficult to accomplish by a remotely-located pilot. Although the cruise missile has proved an effective weapon against highly-defended targets deep into enemy territory, this type of sophisticated weapon is not cost-effective for every strike mission, even as a munitions carrier. In simple terms, automation, miniaturisation, and real-time data transmission are unlikely to progress sufficiently fast, for the present manned fighters to be replaced by a UAV for all missions. Also an all-UAV fleet would become vulnerable to jamming of data links, attack of command centres, etc. creating the risk of losing fleet-wide effectiveness by disabling one link, unless extensive and expensive redundancy is maintained. At least one more generation of manned fighters may be needed, before the pilot can be left elsewhere, out of harm's way. That or those fighter generations may need much improved survivability, making stealth essential. The shifting of some of the missions to UAVs, and the possible retention of existing aircraft for lower risk missions, would reduce the numbers of new stealth fighters needed in the inventory. This raises the question of whether it makes sense for an Air Force to operate a small number of very expensive aircraft: on one hand they are essential, but on the other the small number exacerbates the high purchase cost, by requiring a large investment in support equipment and infrastructure, to be used by a small fleet.

8.2. Long-Term Trends

As fighter unit costs increase, and national fleets become smaller, a long-term trend towards pooling of resources and mutual interdependence is almost inevitable, unless missions or roles shift, and can be performed by less expensive platforms.

8.2.1. Pooling of Resources

The pooling of resources is not new, and may become more widespread in the future. The NATO AWACS fleet is a pool among member nations; only the United States, Britain and France, have national AWACS fleets, the latter two relatively small. It has been decided that ECM for all US forces will be provided by EA-6Bs of the USN, following the retirement of USAF EF-111; although the latter aircraft had the advantage of being supersonic, it was available in insufficient numbers to satisfy all needs. The four of the European Air Forces which first selected the F-16, namely, Netherlands, Belgium, Denmark and Norway, have followed up joint production, by a joint scheme for major logistic support, and a MLU (Mid-Life Update) coordinated with the USAF. Outside the aeronautical world, the Belgian and Dutch navies have decided to merge their fleets: are they being precursors, as the Benelux preceded the European Community?

8.2.2. Mutual Dependence

The once uncompromised principle of national sovereignty and independence in defence matters has already given way to increasing mutual interdependence, and not only through treaties and alliances, like NATO, WEU or EU. The economic need to develop jointly major weapon systems like Tornado or the EF 2000, is a de facto mutual dependence; in this respect, having separate national production lines, does not change the dependence on systems or components produced in other partner countries. The fact that multinational programmes are becoming the rule is reflected at the requirements side by the emerging EAA (European Armaments Agency); on the industry side, the example of the civil Airbus consortium going into a true single, multi-national company, may expand to include military programmes, for the aeronautical industry has the same problems. On the operational side, recent major interventions, like the Gulf War and Bosnia, have seen multinational deployments, often with some specialisation, e.g. one of the air forces may provide most of the electronic countermeasures or defence suppression, so that there is mutual dependence to a high degree. The formation of Eurocorps points to more permanent multinational groupings of forces. All this is still far from a single unified command or a squadron with fighters of several nationalities or mixed ownership. Whether or not this level of integration will be reached, it is clear that the trend towards mutual dependence is increasing, even if the military or defence policy is one of the most jealously guarded national prerogatives, and hence difficult to harmonise at European level.

The emergence of a more cohesive European pillar of NATO, as concerns requirement and operations, may ultimately lead to a more balanced transatlantic arms trade balance, and even to transatlantic industrial groupings or companies.

Whether the pooling of resources, the joint development, and the specialisation of tasks, will ultimately reach a transatlantic proportion, is a more difficult question, for it will be very difficult for the United States to accept that some essential capability lies elsewhere, although Europe has for so long depended on the American defence umbrella.

8.2.3. Shift of Missions

In the very long term, much as the likelihood of global war has receded, the risks of regional conflicts may also reduce, although in the near future regional tensions are likely to get worse before they get better. Even within a perhaps utopian long-term vision of a world without major global or regional conflicts, the risks of social and ethnic tensions and terrorism and organised violence, are likely to remain. These 'unconventional, local' 'defence' missions are likely to grow in importance relative to conventional warfare, much as 'local conflicts and peacekeeping' have gained in importance relative to the readiness for global war. To counter effectively terrorism and similar violence, may require the kind of advanced systems and technologies used in the aerospace world, but at a smaller component level, e.g. using similar sensor and processing technology, etc. The skill of integrating advanced systems in complex platforms will remain useful, also in the civil side concerning mass transport, and in the space sector, including satellite operations and space exploration.

8.3. The Second Century of Aviation

Aviation is one of, or perhaps, the technology of the XXth century. Nearly a century from the first flight of an aircraft, it is possible to project technological evolution a further quarter-century ahead, to 2020; beyond that technological trends may still be identified, but their maturation dates are uncertain and unexpected developments could arise. Keeping in mind that technology maturation takes one or two decades, we can expect that most of what will be operational by 2020, will be on the drawing board or laboratory now. Trying to look at a scale of centuries rather than decades, it could be argued that aeronautics of the XXth century was inspired by birds, and that of XXIst could evolve too in the direction of insects. Clearly the aircraft with a large payload has a lasting future, at least as transport; however one could see the emergence of other missions, which are feasible with a small payload, paving the way to the miniature aircraft, without loss of sophistication.

One possible avenue of such development could start with decoys. The MALD (Miniature Air Launched Decoy), with a span of less than 0,1 m, length less than 0,38 m, powered by 20 Kg thrust turbojet, can fly an F-16 profile, and produce a comparable radar image. If one were to consider the development of miniature sensors, then this decoy could become a reconnaissance platform. If a low-weight warhead, e.g. a non-lethal type optimised for clever disruption of communications, this would become an offensive weapon, perhaps with an anti-radar function. The projected cost of MALD, no more than US$ 30,000, suggests that miniature aircraft could break the cost spiral, well beyond the current concept of UTA.

Another example of hardware development in a similar direction is LOCAAS (Low-Cost Autonomous Attack System) with a similar cost to MALD, and comparable propulsion requirements. This weapon weighs less than 100 lb, and has a stand-off range up to 100 n.m. It fits into a 7x10x20" space, with folding wing, with 36" unfolded span. In spite of its small size and weight, by the use of LADAR (Laser Detection and Ranging) or 'laser radar', it can discriminate targets with sufficient accuracy to choose which form of the multi-mode warhead to detonate: a long rod against a battle tank, a single slug against a lightly armoured target, or multiple fragments against soft or area targets, like trucks, radar dishes or missile launchers.

These miniature decoys and stand-off weapons will initially augment the capability of manned and unmanned aircraft, allowing them to carry a larger complement. Ultimately, with further development, they could become fully autonomous systems, with no need for a launch aircraft.

The issues of defence against miniature aircraft, and risks of proliferation, may grow in inverse proportion to their size. Whatever the implications, with all the advances not just in microelectronics, but also micromechanics, the miniature aircraft may become a more able performer, while consuming far less resources - this is a trend forthcoming generations are likely to watch.

9. APPENDIX

The appendices contain information about post-war combat aircraft in three groups: (i) fighters; (ii) fighter-bombers; (iii) bombers.

9.1. Fighters

The seven post-war generations of fighters are listed, with photos and specifications.

9.1.1. Fighter Aircraft per Country of Origin

The Table VII lists the main types of fighter aircraft of the seven post World War II generations, according to the country where they were developed.

TABLE VII
Seven Post-War Generations of Fighters

Country	Generation I: Subsonic	Generation II: Transonic	Generation III: Supersonic [III': Transonic]
USA	Lockheed F-80 Shooting Star Northrop F-89 Scorpion Republic F-84 Thunderjet McDonnell F1H Phantom I McDonnell F2H Banshee Grumman F9F Panther	North American F-86 Sabre Republic F-84F ThunderStreak North American FJ-1 Fury Chance Vought F7U Cutlass Grumman F9F Cougar	North American F-100 Super Sabre Convair F-102 Delta Dagger Grumman F-11F Tiger [McDonnell F3H Demon] [Douglas F4D Skyray]
URSS	Mikoyan-Gurevich Mig-9 Fargo Yakovlev Yak-17 Feather Yakovlev Yak-23 Flora	Mikoyan-Gurevich Mig-15 Fagot Mikoyan-Gurevich Mig-17 Fresco Yakovlev Yak-25 Flashlight	Mikoyan-Gurevich Mig-19 Farmer Yakovlev Yak-28 Firebar
UK	Gloster Meteor De Havilland Vampire Armstrong Whitworth Sea Hawk Supermarine Attacker	Hawker Hunter Supermarine Swift	[Gloster Javelin] [De Havilland Sea Vixen] [Supermarine Scimitar]
FRANCE	Dassault Ouragan	Dassault Mystère	Dassault Super Mystère [Dassault Etendard]
SWEDEN	Saab 21R	Saab 29 Tunnan	[Saab 32 Lansen]
OTHERS	Avro CF-100 (Canada)		[Hindustan HF-24 Marat] (India) Shenyang A-5 Fantan (China)

Country	Generation IV: Bisonic	Generation V: Multi-role [V' - Trisonic] [V'' - Interdiction]	Generation VI: High-Agility [VII: Stealth]
USA	McDonnell F-101 Voodoo Lockheed F-104 Starfighter Republic F-105 ThunderChief Convair F-106 Delta Dart Vought F-8 Crusader Northrop F-5 Freedom Fighter	McDonnell F-4 Phantom II [Lockheed SR-Z1 Blackbird] [General Dynamics F-111 Aardvark]	Grumman F-14 Tomcat McDonnell Douglas F-15 Eagle General Dynamics F-16 Falcon McDonnell Douglas F-18 Hornet [Lockheed F-22 Lightning II]
URSS	Mikoyan-Gurevich Mig-21 Fishbed Sukhoi Su-7 Fitter Sukhoi Su-9 Fishpot Tupolev Tu-28 Fiddler	Mikoyan-Gurevich Mig-25/27 Flogger Sukhoi Su-2 Fitter Sukhoi Su-25 Flagon [Mikoyan-Gurevich Mig-25/31 Foxbat/Foxhound] [Sukhoi Su-24 Fencer]	Mikoyan-Gurevich Mig-19 Fulcrum Sukhoi Su-27/30 Flanker [Mikoyan-Gurevich I - 400]
UK	English Electric Lightning	{Panavia Tornado} (with Germany, Italy)	Eurofighter 2000 (with Germany, Italy, Spain)
FRANCE	Dassault Mirage III/V	Dassault Mirage F Dassault Mirage 2000	Dassault Rafale
SWEDEN	Saab 35 Draken	Saab 37 Viggen	Saab 39 Gripen
OTHERS	Shenyang J-8 Finback (China)		

9.1.2. Seven Generations of Fighters

The following photos depict the main examples of the seven generations of fighters.

PHOTOS:

Generation I – Subsonic Fighters

a. Lockheed F-80C Shooting Star
b. Northrop F-89J Scorpion
c. Republic F-84G Thunderjet
d. McDonnell F1H Phantom I
e. McDonnell F2H Banshee
f. Grumman F9F Cougar
g. De Havilland Vampire FB.30
h. Gloster Meteor NF.14
i. Supermarine Attacker S.1
j. Armstrong Whitworth Sea Hawk Mk.100
k. Dassault MD.450 Ouragan
l. Avro CF-100 Mk.4B

Generation II - Transonic Fighters:

a. North American F-86F Sabre
b. North American FJ4 Fury
c. Republic F-84F Thunderstreak
d. Grumman F9F8T Cougar
e. Chance Vought F7U1 Cutlass
f. Fiat G.91R1
g. Mikoyan-Gurevich Mig-15 Fagot
h. Mikoyan-Gurevich Mig-17PFM SP-6 Fresco
i. Hawker Hunter F.6
j. Supermarine Swift FR.5
k. Dassault Mystère IVA
l. Saab J29F Tunnan

Generation III - Supersonic Fighters (* transonic):

a. North American F-100D Super Sabre
b. Convair F-102A Delta Dagger
c. Grumman F11F1 Tiger
*d. McDonnell F3H2 Demon
*e. Douglas F6D1 Skyray
f. Mikoyan-Gurevich Mig-19PF Farmer
*g. Gloster Javelin FAW.8
*h. De Havilland Sea Vixen FAW.2
i. Supermarine Scimitar F.1
j. Dassault Super Mystère B.2
*k. Dassault Etendard IVM
*l. Saab J32B Lansen

Generation IV - Bissonic Fighters:

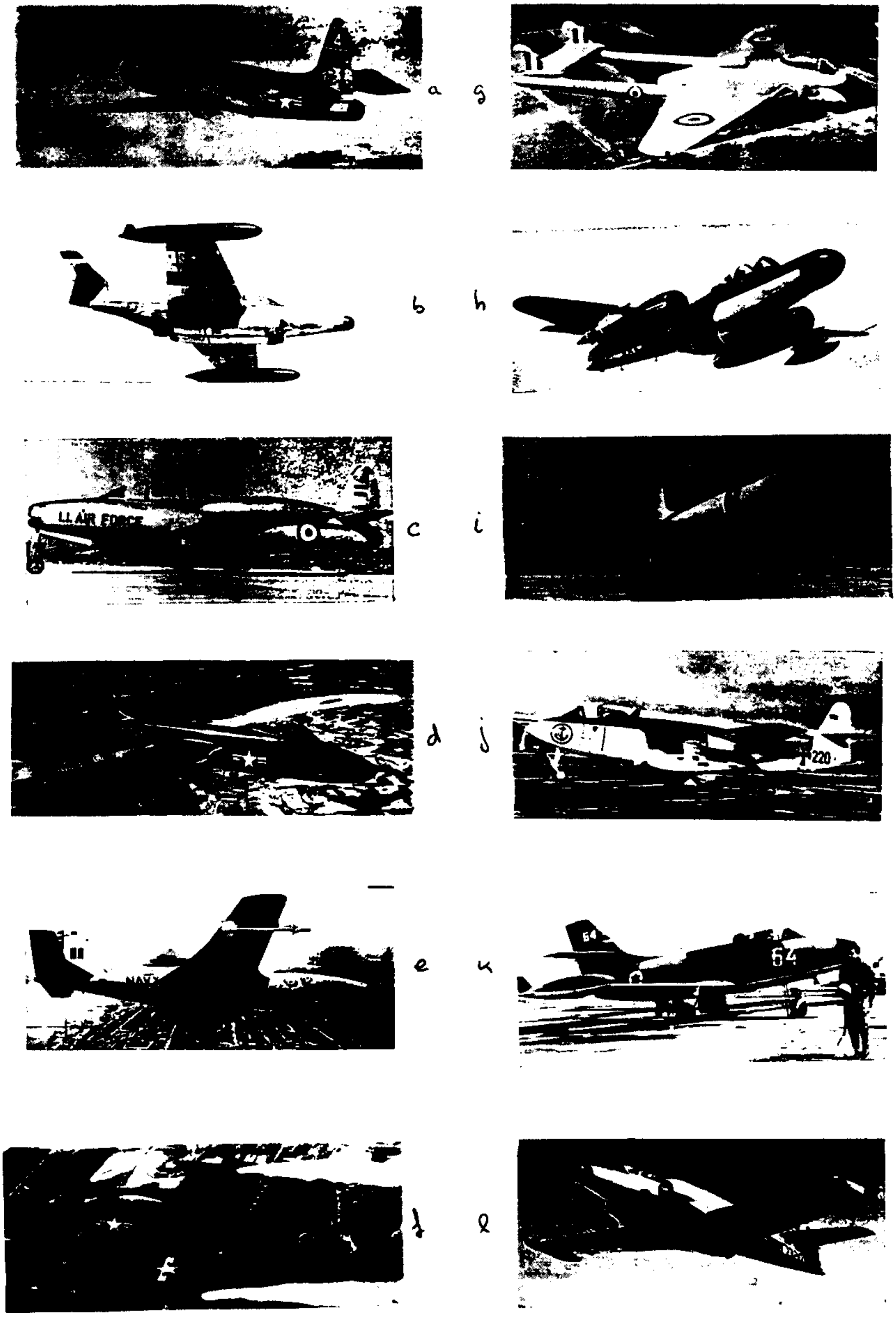
a. McDonnell F-101C Voodoo
b. Lockheed F-104G Starfighter
c. Republic F-105D Thunderchief
d. Convair F-106A Delta Dart
e. Northrop F-5E Tiger II
f. Chance Vought F8U2N Crusader
g. Mikoyan-Gurevich Mig 21MF Fishbed-J
h. Sukhoi Su-11 Fishpot-C
i. Tupolev Tu-28P Fiddler
j. English Electric Lightning F.1
k. Dassault Mirage IIIC
l. Saab J35B Draken

Generation V - Multi-role Fighters (* trisonic; **interdiction):

a. McDonnell F-4M Phantom II FGR.2
*b. Lockheed YF-12A
**c. General Dynamics FB-111A Aardvark
d. Sukhoi Su-15 Flagon-D
*e. Mikoyan-Gurevich Mig-23 Flogger-G
f. Sukhoi Su-22 Fitter-F
g. Saab JA37 Viggen
h. Mikoyan-Gurevich Mig-23 Foxbat-A
**i. Sukhoi Su-24 Fencer-D
**j. Panavia Tornado GR.1
k. Dassault Mirage 2000
l. Dassault Mirage F.1C

Generation VI - High-Agility Fighters (*Generation VII - Stealth):

a. Grumman F-14A Tomcat
b. McDonnell Douglas F-15C Eagle
c. General Dynamics F-16A Falcon
d. McDonnell Douglas F/A-18A Hornet
*e. Lockheed F-22A Lightning II
f. Mikoyan-Gurevich Mig-29 Fulcrum-A
g. Sukhoi Su-27 Flanker-B
h. Dassault Rafale-A
i. Eurofighter 2000
j. Saab JAS39 Gripen



Generation I - Subsonic Fighters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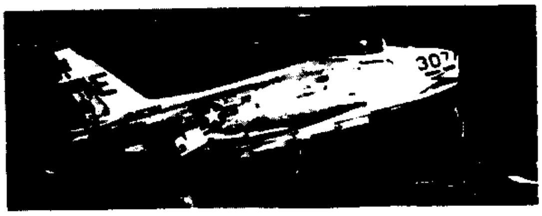

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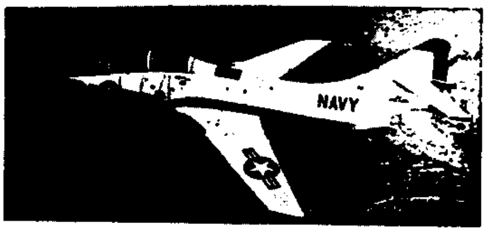

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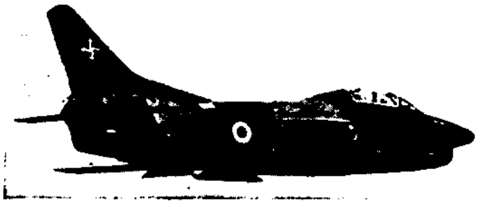
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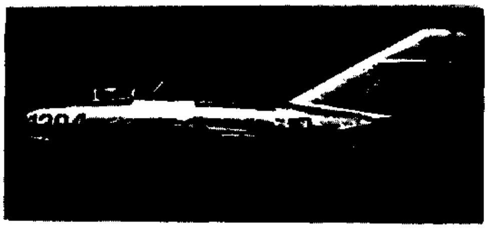
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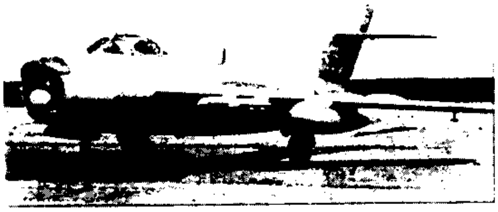
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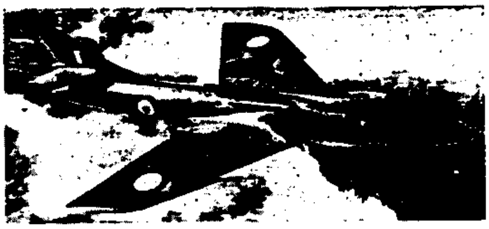
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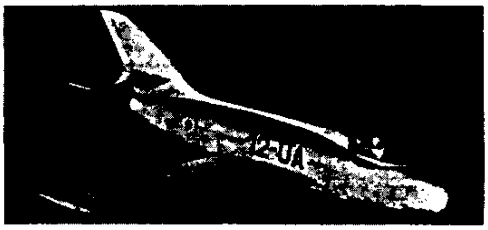

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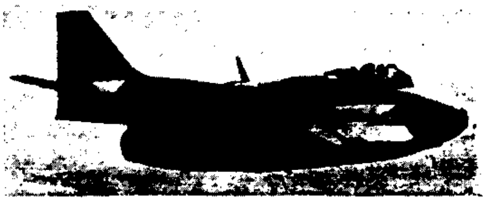
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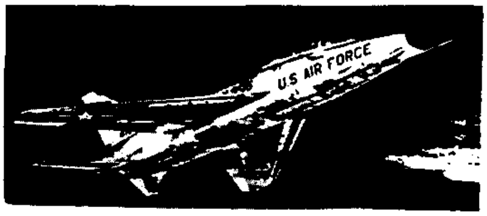
Generation II - Transonic Fighters



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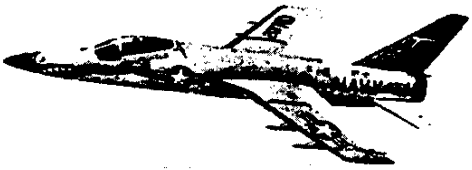

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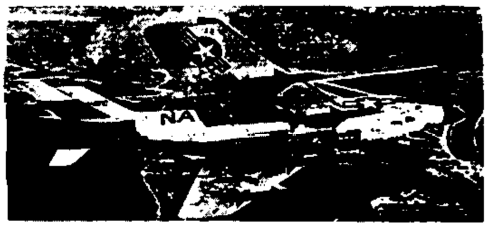

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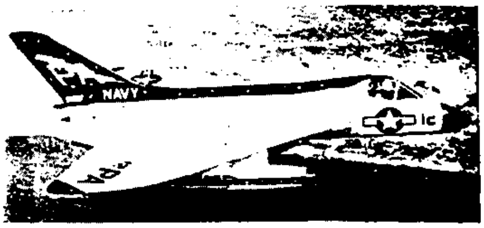

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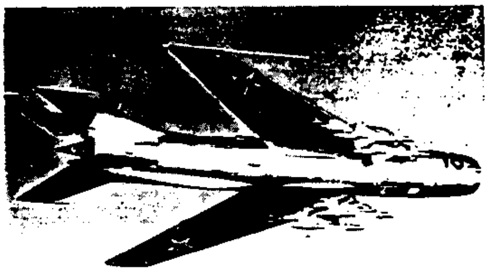

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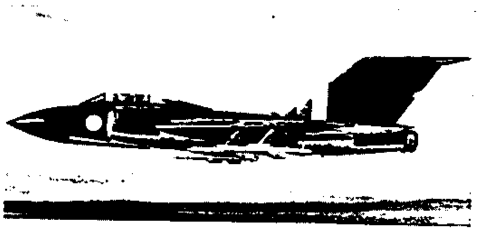

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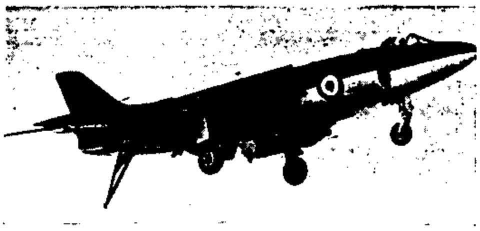

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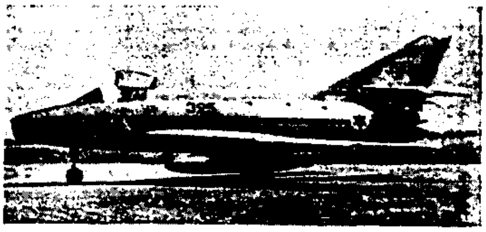

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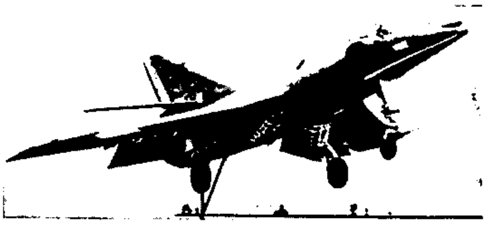

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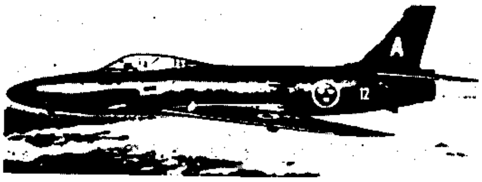

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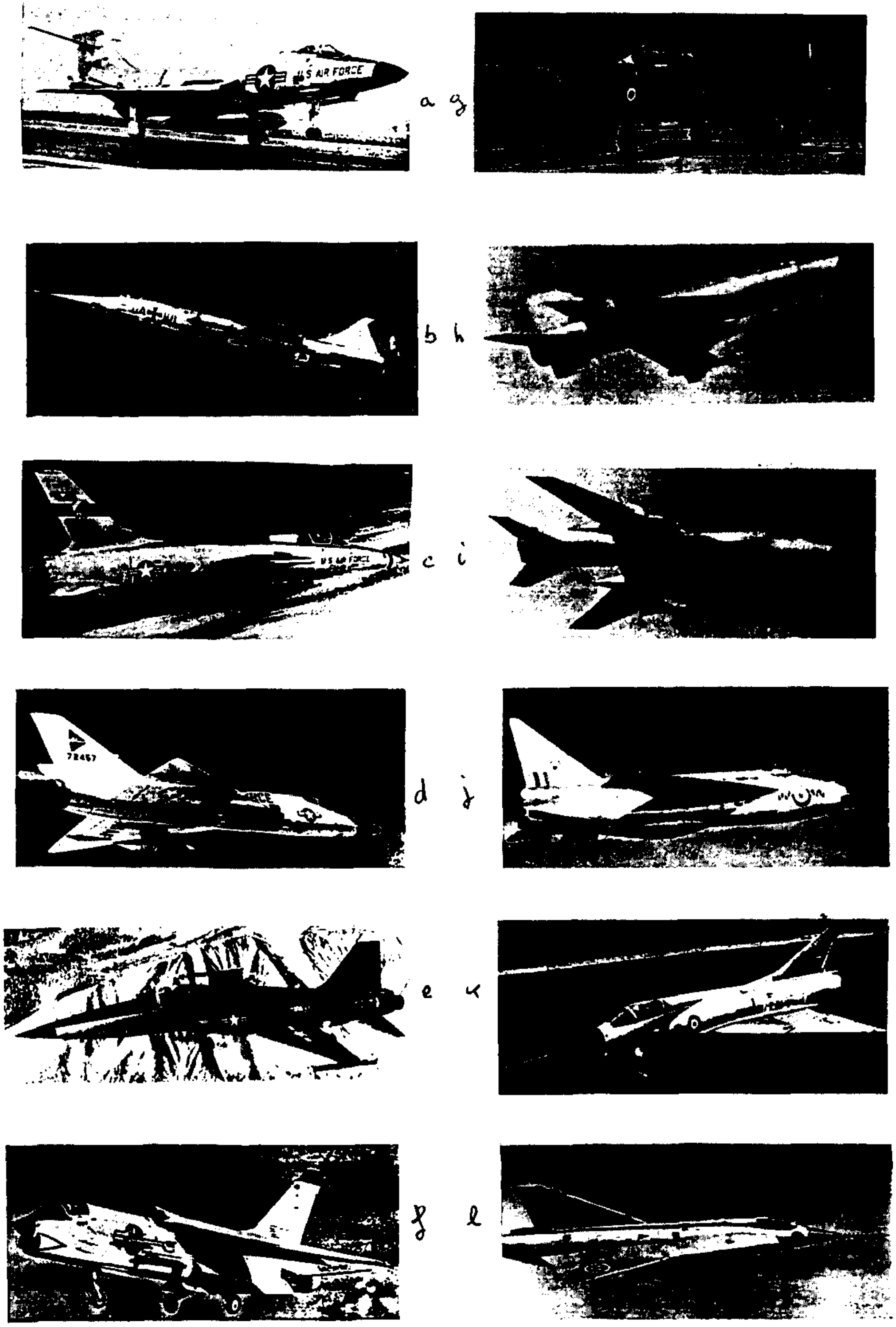
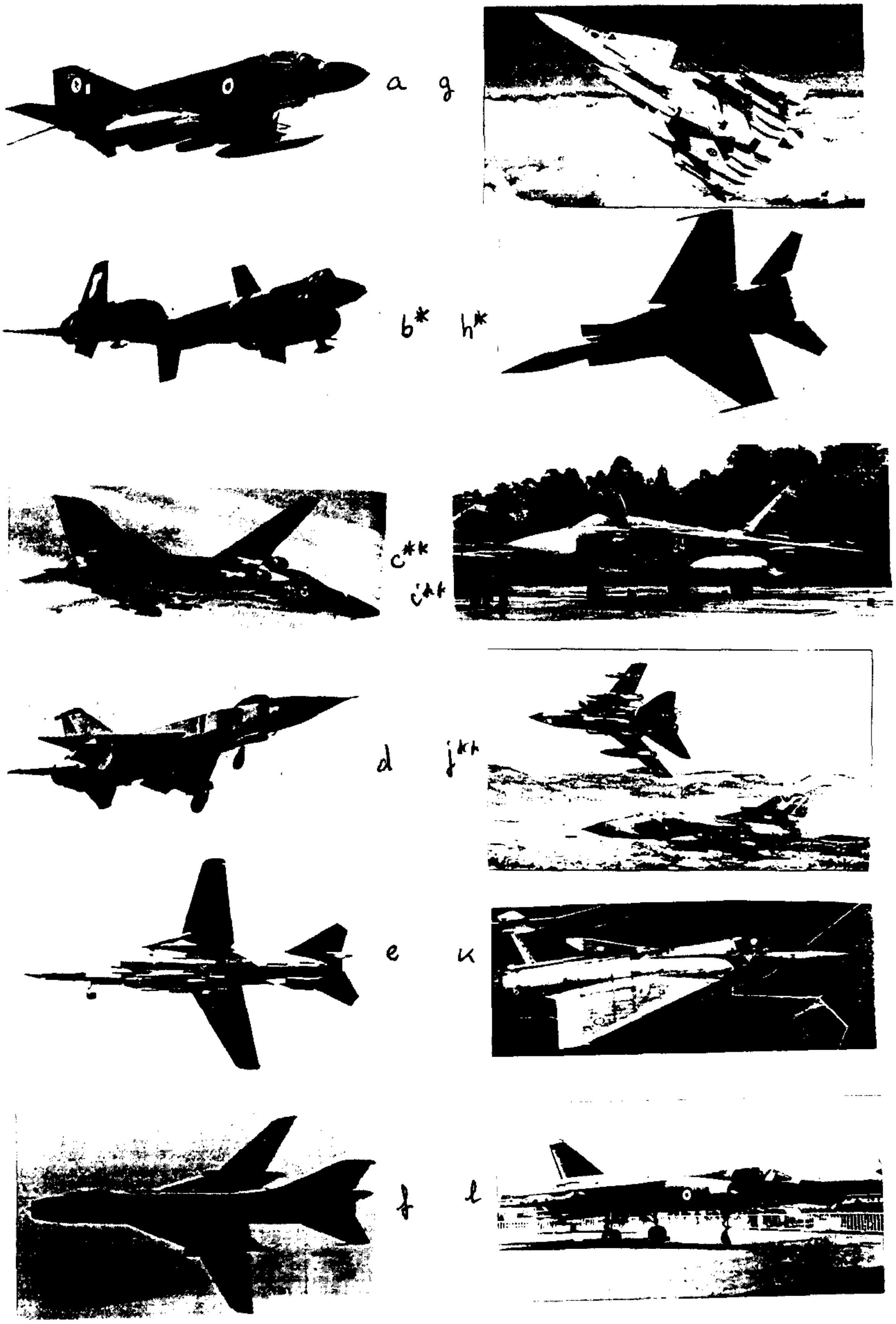
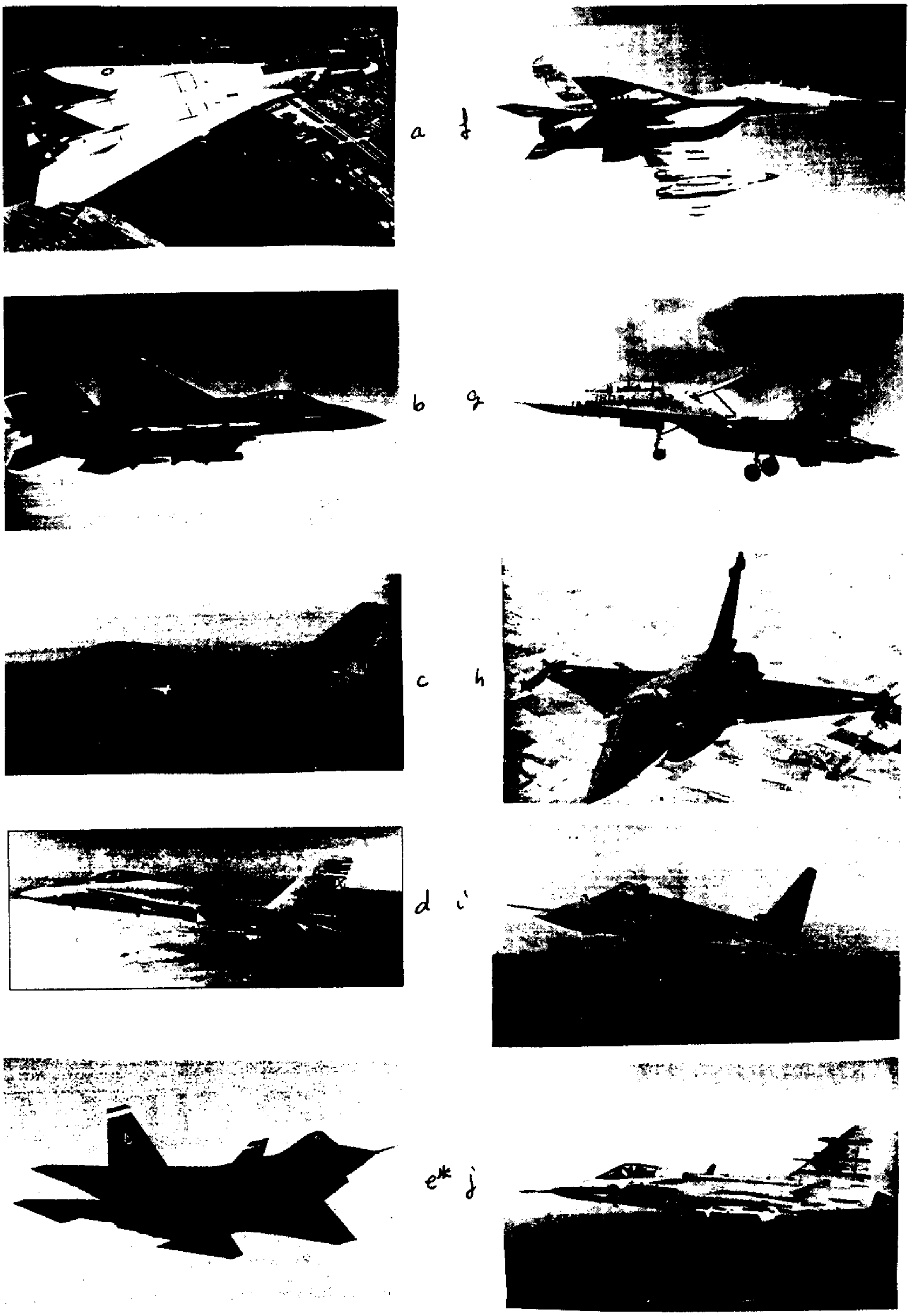
Generation III - Supersonic Fighters (* transonic)



Generation IV - Bissonic Fighters



Generation V - Multi-Role Fighters (*trisonic; **interdiction)



Generation VI - High-Agility Fighters (*Generation VII – Stealth)

9.1.3. Specification Tables for Fighters

The specification tables have the standard format:

AIRCRAFT
- manufacturer
- designation
- name or model

ENGINE
- manufacturer
- designation
- thrust in Kg, without/with afterburning

DIMENSIONS
- length overall (m)
- span (m)
- height overall (m)
- wing area (m^2)

WEIGHTS
- empty (Kg)
- maximum (Kg)
- fuel - total (l)
- fuel - internal (l)
- fuel - external (l)

PERFORMANCE
- Maximum speed (Km/h)
- at altitude (m)
- Mach Number
- rate-of-climb at sea level (m/s)
- ceiling (m)
- radius of action (Km)
- with warload (Kg)
- maximum range (Km)

ARMAMENT
- guns (number x calibre in mm)
- rockets (number x calibre)
- bomb load (Kg)
- air-to-air missiles
- air-to-surface missiles

I - SUBSONIC FIGHTERS

AIRCRAFT													
manufacturer	Lockheed	Republic	Grumman	McDonnell	Northrop	McDonnell	De Havilland	Gloster	Hawker	Mikoyan	Yakovlev	Dassault	Avro
designation	F-80C	F-84G	F9F2	F1H1	F-89D	F2H3	DA-100	Meteor		Mig-9MFR	Yak-23	MD.450	CF-100
name or model	Shooting Star	Thunderjet	Panther	Phantom I	Scorpion	Banshee	Vampire	F-6	Sea Hawk	I-208	Flora	Ouragan	MK.4B
ENGINE													
manufacturer	Allison	Allison	P&W	Westinghouse	Allison		De Havilland	Rolls Royce	Rolls Royce	Kolosov		Rolls Royce	Orenda
designation	J33 A-23	J33-A-29	J48-P-8	J30-WE-20	J35-A-33A	J34-WE-34	Goblin 3	Derwant 8	Nene 102	RD-2	RD-500	Nene 104	Orenda
thrust (kg) without/with afterburning	2359	2540	2601	2x726	2x2467/3266	2x1474	1520	2x1633	2449	2x1000	1588	2270	2x3300
DIMENSIONS													
Length overall (m)	10,49	11,60	11,35	11,81	16,40	14,68	10,49	13,11	12,09	9,83	9,14	10,75	16,52
span (m)	11,81	11,09	10,74	12,43	18,41	14,78	12,19	13,26	11,89	10,00	8,53	13,16	16,34
height overall (m)	3,42	3,83	3,50	4,32	5,33	4,41	2,69	4,22	2,64	3,23		4,14	4,92
wing area (m^2)	22,07	24,15	23,22	25,64	56,29	27,31	24,3	32,5	25,8	18,20		23,8	50,17
WEIGHTS													
empty (kg)	3819	5032	4220	3031	11428	5980	3290	4820	4409	3356	2000	4147	10071
maximum (kg)	7646	10671	8842	5459	19426	11437	5606	6648	7348	5069	3341	7900	16330
fuel-total (1)													
fuel-internal (1)	1609	1711	3494	1419	5901	5488				1300			
fuel-external (1)	1249	4x871		1125					4x409			2x625	
PERFORMANCE													
Maximum speed (km/h)	956	1001	847	885	904	933	866	885	901	965	914	830	1046
at altitude (m)	0	0	6706	9144	12192	0	1524	9144	10173	5000		12000	3048
Mach number	0,783	0,818	0,752	0,744	0,852	0,763	0,770	0,812	0,846			0,782	0,895
rate of climb at sea level (m/s)	34,90	30,79	26,11	21,48	62,48	30,47	20,61	35,56	28,96		340	43,0	40,64
Ceiling (m)	13442	12344	13594	12527	15392	14204	12192	13412	13564	13000	14798	13000	15240
radius of action (km)	531	869	451	555	313		644	555	467			451	1046
with warload (kg)													
maximum range (km)	2221	3219	2177	1609	1456	2762	1843	1931	1239	830		920	3701
DEVELOPMENT													
First flight	9.1.44	28.2.46	24.11.47	26.1.45	16.8.48	11.1.47	1946	15.3.43	2.10.47	24.3.46	24.4.46	28.2.49	
Production	+8543	4457	>437	162	896	895	>4000	>2297	>527				>563
ARMAMENT													
guns (number x caliber)	6x12,7	6x12,7	4x20	4x12,7	6x20	4x20	4x20	4x20	4x20	1x37 + 2x23	2x13	4x20	8x12,7
Rockets: no x mm	8x70	32x127	6x127		104x70	8x70		16x76	48x76			16x105	104x70
Bomb load (kg)	2x454	1814	2x227		1451	454	907	2x454	4x227			1006	
air-to-air missiles					6 Falcon								
air-to-surface missiles													

II - TRANSONIC FIGHTERS

AIRCRAFT										
manufacturer	North American	Republic	North American	Chance Vought	Grumman	Mikoyan-Gurevich	Mikoyan-Gurevich	Hawker	Saab	Dassault
designation	F-86F	F-84F	FJ-4	F703M	F9F8	Mig-15 SV	Mig-17F	Hunter	J29F	Mystère
name or model	Sabre	ThunderStreak	Fury	Cutlass	Cougar	Fagot	Fresco	F6	Tunnan	IV A
ENGINE										
manufacturer	General Electric	Wright	Wright	Westinghouse	Pratt & Whitney	Klinov	Klinov	Rolls Royce	Svenska Flygmotor	Hispano Suiza
designation	J47-6E-27	J65-W-3	J65-W-16A	J46-WE-8	J48-P-8A	RD-45F	KK-1F	Avon 203	RM 2B	Verden 350
thrust (kg) without/with afterburning	2708	3275	3493	2x2086/2597	3855	2700	2600/3380	4559	2800	3500
DIMENSIONS										
Length overall (m)	11,27	13,23	11,43	13,13	12,85	10,10	11,26	13,98	10,11	12,85
span (m)	11,91	10,34	11,91	12,10	10,51	10,09	9,63	10,26	11,00	11,12
height overall (m)	4,26	4,57	3,86	4,45	3,73	3,70	3,80	4,01	3,73	6,60
wing area (m^2)	26,75	30,2	31,49	46,07	31,30	20,60	22,60	32,4	27,9	31,35
WEIGHTS										
empty (kg)	**4906**	**6397**	**5992**	**8840**	**5382**	**3523**		**5919**	**4491**	**5874**
maximum (kg)	**9349**	**12701**	**10750**	**16783**	**11232**	**5405**	**6069**	**10886**	**8000**	**9095**
fuel-total (1)										
fuel-internal (1)	1646		3179	5942	4023	1225	1170		1305	2600
fuel-external (1)	1514	4x871	1515	1969	1130		2x400	4x455	2x400	2x1250
PERFORMANCE										
Maximum speed (km/h)	1107	979	1094	1091	1033	1031	1071	1009	1059	991
at altitude (m)	0	10668	0	0	0	5000	10000	10973	1524	12000
Mach number	0,905	0,919	0,894	0,893	0,845			0,947	0,889	0,930
rate of climb at sea level(m/s)	47,25	41,66	38,92	53,33	29,22	55,00	65	88,90	60,00	45,00
Ceiling (m)	14630	12878	14265	13838	12802	15200	16600	16276	15500	13716
radius of action (km)	745	724		523		386	515	402		459
with warload (kg)										
maximum range (km)	2120	3724	3251	>2000	2111	1650	2020	3058	2700	1690
DEVELOPMENT										
First flight	10.1.47	3.7.50	27.11.46	1.3.50		30.12.47	1950	20.7.51	1.10.48	28.10.52
Production	7822	3430	1166	310		16500		1928	661	421
ARMAMENT										
guns (number x caliber)	6x12,7	6x12,7	4x20	4x20	4x20	2x33+1x37	2x33+1x37	4x30	4x20	2x30
Rockets: no x mm	6x70					16x55	32x55	148x51	24x75	76x37
Bomb load (kg)	907	3171	1360	1814	907	907	500	2x454	2x250	2x454
air-to-air missiles	2 Sidewinder		2 Sidewinder	4 Sidewinder					2 Sidewinder	
air-to-surface missiles										

III - SUPERSONIC FIGHTERS

AIRCRAFT													
manufacturer	North American	Convair	Grumman	McDonnell	Douglas	Mikoyan-Gurevich	Yakovlev	Gloster	De Havilland	Supermarine	Dassault	Dassault	Saab
designation	F-100 D	F-102 A	F11 F	F3 H2	F4 D1	Mig-19 S	Yak-25 P	Javelin	Sea Vixen	Scimitar	Super Mystère	Etendard	J 32 B
name or model	Super-Sabre	Delta Dagger	Tiger	Demon	Skyray	Farmer	Firebar	FAW.9	FAW.2	F.1	B.2	Super	Lansen
ENGINE													
manufacturer	Pratt & Whitney	Pratt & Whitney	Wright	Allison	Pratt & Whitney	Tumanski	Tumanski	Bristol Siddeley	Rolls Royce	Rolls Royce	Svenska	Svenska	Volvo
designation	J57-P-25A	J57-P-25	J65-W-18	J71-A-2E	J57-P-8	RD-9B	RD-11	Sapphire 20	Avon 208	Avon 202	Atar 101 G	Atar 8K-50	RM6A
thrust (kg) without/with afterburning	5307/7688	5307/7802	3629/4989	4400/6690	4627/7258	2x2600/3250	2x4600/6200	2x4990/5580	2x4536	2x5103	3400/4500	5110	5000/6500
DIMENSIONS													
Length overall (m)	15,24	20,82	13,69	17,98	13,81	12,54	22,95	17,24	16,98	16,86	14,05	14,31	14,94
span (m)	11,81	11,60	9,65	10,76	10,18	9,60	12,50	15,85	15,24	11,32	10,50	9,60	13,00
height overall (m)	4,94	6,45	4,03	4,44	3,96	4,02	3,96	4,88	3,34	4,64	4,52	3,86	4,64
wing area (m^2)	37,16	64,56	23,22	48,21	51,74	25,00		86,21	60,20		35,02	18,40	37,40
WEIGHTS													
empty (kg)	9526	8777	6486	10040	7268	5760					6985	6450	7500
maximum (kg)	15800	14288	10922	15377	12701	8700	18500	17240	15876	18140	10000	12000	13500
fuel-total (1)													
fuel-internal (1)	6582	3974	3970	2983	2422	1800						3270	3500
fuel-external (1)	1514	1741		2717	2271	2x760		2x1125	2x683	2x1125	2x820	2x600	
PERFORMANCE													
Maximum speed (km/h)	1390	1328	1170	1041	1118	1452	1225	1118	1094	1142	1195	1205	1014
at altitude (m)	10973	10953	10668	10608	10668	10000	12000	3048	3048	3048	12000	0	10973
Mach number	1,310	1,252	1,102	0,981	1,053	1,368	1,155	0,950	0,930	0,97	1,126	0,986	0,955
rate of climb at sea level(m/s)	96,52	65,60	26,07	65,00	92,97	115,00	142,24				88,90	10	100
Ceiling (m)	14539	16276	12771	10683	16764	17500	16765	18288	15240		17000	16000	16000
radius of action (km)	430	315	890	900	783	695	885	900		414	434	650	800
with warload (kg)													
maximum range (km)	3211	2401	2237	2205	1963	2200				2414	1174	2000	3200
DEVELOPMENT													
First flight	25.5.53	18.9.48	30.7.54	24.12.53	5.6.54	1953	1955	1956	20.3.57	1956	2.3.55	21.5.58	7.1.57
Production	2294	949	202	299	419						206	170	>300
ARMAMENT													
guns (number x caliber)	4x20		4x20	4x20	4x20	2x23+1x37	2x23	2x30		4x30	2x30	2x30	4x30
Rockets: no x mm		24x70			72x70	16x55		37	28x50	48x56	35x68	72x68	78x75
Bomb load (kg)	3401			2721		2x250			4x227	3628	2x500	2100	1500
air-to-air missiles	2 Sidewinder	6 Falcon	4 Sidewinder	4 Sidewinder	2 Sidewinder	4 Alkali	2 Anab	4 Firestreak	4 Red Top			4 Magic	4 Sidewinder
air-to-surface missiles									4 Bullpup	4 Bullpup		2 Exocet/ 1 ASMP	2 Bofors 04C

IV - BISONIC FIGHTERS

AIRCRAFT													
manufacturer	McDonnell	Lockheed	Republic	Convair	Vought	Northrop	Mikoyan-Gurevich	Sukhoi	Sukhoi	Tupolev	English Electric	Dassault	Saab
designation	F-101 B	F-104 C	F-105 D	F-106 A	F 802 NE	F-5E	Mig-21 MF	Su-7	Su-9	Tu-28P	Lightning	Mirage	J 35 F
name or model	Voodoo	Starfighter	ThunderChief	Delta Dart	Crusader	Freedom Fighter	Fishbed 5	Fitter	Fishpot	Fiddler	F.6	III C	Draken
ENGINE													
manufacturer	Pratt & Whitney	General Electric	Pratt & Whitney	Pratt & Whitney	Pratt & Whitney	General Electric	Tumansky	Lyulka	Lyulka	Mikulin	Rolls Royce	Svenska	Volvo
designation	J53-P-13	J79-GE-11A	J75-P-19W	J75-P-17	J57-P-20A	J85-GE-21	R-13	AC-7	AC-7	M-209	Avon 301	Atar 96	RM6C
thrust (kg) without/with afterburning	2x4627/6804	4536/7076	7802/12020	7802/11113	4853/8165	2x1588/2268	4070/6490	7000/10000	7000/10000	2x8165/9980	2x5756/7421	4250/6000	5765/7802
DIMENSIONS													
Length overall (m)	20,54	16,66	19,58	21,56	16,53	14,45	12,29	16,8	17,1	30,0	16,84	13,85	14,05
span (m)	12,09	6,62	10,64	11,65	10,87	8,53	7,15	9,8	7,9	19,8	11,62	8,20	9,42
height overall (m)	5,48	4,08	5,99	6,17	4,80	4,06	4,13	4,9	4,9	6,1	5,97	4,20	3,87
wing area (m^2)	34,18	18,21	35,76	58,64	34,83	17,27	23,00		39,5	74	42,7	34,0	49,22
WEIGHTS													
empty (kg)	11326	6348	12474	10726		4392	5350	5700	5900	21950		5113	7425
maximum (kg)	22860	13172	23835	18975	15422	11188	9400	13830	13150	45400	22700	11800	12160
fuel-total (l)													
fuel-internal (l)	8861	3395	10257	5456	6128	2562	2200					2200	2864
fuel-external (l)	5748	2222	4883*			3123	3x490	2x600	2x600		2728	2x1700	2x523
PERFORMANCE													
Maximum speed (km/h)	1624	1334	2285	2454	1802	1743	2230	1700	1915	1850	2410	2230	2124
at altitude (m)	10668	12192	11582	12192	12192	10973	13000	10973	12192	10973	12192	12192	12192
Mach number	1,530	2,195	2,154	2,313	1,698	1,643	2,102	1,60	1,80	1,74	2,27	2,098	1,998
rate of climb at sea level(m/s)	224,0	254,0	175,27		203,2	175,27		254	137,2	125	254	203,2	200,0
Ceiling (m)	17008	16764	14783	17374	17678	16307	18200		15760	18290	17300	16490	16764
radius of action (km)	1480	821	626	586	930	445	370	320	320	1610		650	563
with warload (kg)							1000						
maximum range (km)	4707	3800	3553	2911	2253	2863	1800	1448	1448	5630	1400	2365	1440
DEVELOPMENT													
First flight	29.9.54	4.3.54	22.10.55	26.12.56	25.3.55	12.7.59	26.3.56	1956	1956	1960	4.9.54	17.11.56	25.10.55
Production	807	2732	809	342	1266	1424					330	>1000	>400
ARMAMENT													
guns (number x caliber)	4x20	1x20	1x20		4x20	2x20	2x30	2x30	2x30	1x30	2x30	2x30	2x30
Rockets: no x mm	12x70		162x70					38x55				72x37	
Bomb load (kg)		1814	6350		2268	3175		907				1814	3100
air-to-air missiles	3 Falcon	4 Sidewinder	4 Sidewinder**	4 Falcon + 1 Genie	4 Sidewinder	2 Sidewinder	4 Atoll		4 Alkali	2 Ash	2 Red Top	1 R 530 2 Magic	4 Falcon
air-to-surface missiles		2 Bullpup	4 Bullpup										

* including 1477 l in bomb bay.

** 2 Genie + 4 Falcon.

V - MULTI-ROLE FIGHTERS (*-TRISONIC; **-INTERDICTION)

AIRCRAFT							*					
manufacturer	McDonnell	Mikoyan-Gurevich	Sukhoi	Sukhoi	Dassault	Saab	Lockheed	*Mikoyan-Gurevich	** General Dynamics	Sukhoi	Dassault	Panavia
designation	F-4E	Mig-23 ML	Su-22	Su-15	Mirage	JA37	YF-12A	Mig-31	F-111F	Su-24MP	Mirage	Tornado
name or model	Phantom II	Flogger-G	Fitter-K	Flagon	F1C	Viggen		Foxhound	Aardvark	Fencer F	2000N	GR.4
ENGINE												
manufacturer	General Electric	Khatchatorov	Lyulka	Lyulka	Snecma	Volvo	Pratt & Whitney	Soloviev	Pratt & Whitney	Lyulka	Snecma	Turbo-Union
designation	J79-GE-17	R-35	AL-21F-3	AL-21F-3	Atar 9K50	RM88	J58	D-30F	JF-30-P 100	AL-21F-3	M53-P2	RB.199-34
thrust (kg) without/with afterburning	2x5384/8119	8550/13000	7800/11250	2x7800	5000/7200	7350	2x14742	2x	2x5670	2x7800	6560/10000	2x3946/67
DIMENSIONS												
Length overall (m)	19,20	15,65	18,75	21,50	15,00	15,45	30,78	22,69	22,40	24,53	14,55	16,72
span (m)	11,70	7,78-13,97	10,00-13,80	9,50	8,40	10,60	16,94	13,46	9,72-19,2	10,36-17,63	9,13	8,60-13,91
height overall (m)	5,02	4,82	5,00	5,00	4,50	5,90	6,63	6,15	5,18	6,19	5,15	5,95
wing area (m^2)	49,23	34,16-37,35	37,0-40,0		25,00	52,20	167,22	61,6	48,77	51,02-55,07	41,0	26,60
WEIGHTS												
empty (kg)	13397	10200			7400	12200	27216		21523	19000	7600	13890
maximum (kg)	27965	17800	19500	15876	14900	22500	77112	46200	43243	39700	17000	27950
fuel-total (1)												
fuel-internal (1)	7509	4250	4550				46253	16350	19057	9764	3904	6393
fuel-external (1)	5090	3x800	4x800	2x600	3x1200			2x2500	9084		4700	3x1500
PERFORMANCE												
Maximum speed (km/h)	2301	2500	2220	2655	2122	2228	3621	3000	2338	1433	2334	2334
at altitude (m)	10973	12192	12192	12192	12192	12192	18288	17500	12192	12192	12192	12192§
Mach number	2,169	2,356	2,09	2,50	2,20	2,10	3,412	2,827	2,204	1,35	2,20	2,20
rate of climb at sea level(m/s)		240			213				218,7		284,33	
Ceiling (m)	18715	18500	15200		20000		24384	20600	17648	17500	16460	
radius of action (km)	958	1150		725	1078	476	1111	720	740	1050	602	1390
with warload (kg)		6 ?			2000	6x227		4 Amos		3000		
maximum range (km)	3034	2820	2300	2415			4828	3300	5436		3335	3890
DEVELOPMENT												
First flight	26.5.55	10.7.67			12.7.66	8.2.67	7.8.63		21.12.64	1.70	20.11.82	5.2.77
Production	4669	1800	>1060		>600	329	2		423		535	977
ARMAMENT												
guns (number x caliber)	1x20	1x23	2x30	1x23	2x30	1x30			1x20	1x23	2x30	2x27
Rockets: no x mm												
Bomb load (kg)	7257		4250		4000	6000			17010	8000	6300	9000
air-to-air missiles	6 Sparrow	6 Apex		2 Anab	2 R530	2 Skyflash	4 AIM-47	4 Amos				
air-to-surface missiles			4 Kerry		1 Martel	2 Bb4E				4 Kerry	ASMP	1 Martel 2 Kormoran

VI - HIGH-AGILITY FIGHTERS (VII - STEALTH FIGHTERS)

AIRCRAFT										*
manufacturer	Grumman	McDonnell Douglas	General Dynamics	McDonnell Douglas	Mikoyan-Gurevich	Sukhoi	Dassault	Euro	Saab	Lockheed
designation	F-14 A	F-15 A	F-16 C	F/A-18 A	Mig-29	Su-27	Rafale D	Fighter	JA539	F-22 A
name or model	Tomcat	Eagle	Falcon	Hornet	Fulcrum	Flanken B		2000	Gripen	Lightning II
ENGINE										
manufacturer	Pratt & Whitney	Pratt & Whitney	Pratt & Whitney	General Electric	Klimov	Lyulka				Pratt & Whitney
designation	TF30 P-412	F100-PW-100	F100-PW-200	F104-GE-400	2X 9040	2X	1892	EJ 200	RM 12	F119-PW-100
thrust (kg) without/with afterburning	2x5670	2x6745	6713/11612	4810/7257	15600/8300	12500	2x8870	2x6120/9185	5500/8210	2x15876
DIMENSIONS										
Length overall (m)	18,89	19,43	15,03	17,06	17,32	21,94	15,30	14,50	14,10	18,92
span (m)	11,63-19,53	13,03	9,45	12,39	11,36	14,70	10,90	10,50	8,40	13,50
height overall (m)	4,87	5,66	5,09	9,64	4,73	5,93	5,34	4,00	4,50	5,00
wing area (m^2)	52,48	56,48	27,87	37,16	38,00		46,00	50,00		78,00
WEIGHTS										
empty (kg)	18176	12247	6895	12701	10900		9060	9750	6622	
maximum (kg)	31102	29938	16057	25402	18500	30000	21000	21000	12473	27216
fuel-total (1)										
fuel-internal (1)	9576	6487	3073	6321	4365		>5325	4000	2268	
fuel-external (1)	2044	6813	1985	3406	3100		6000	3500		
PERFORMANCE										
Maximum speed (km/h)	2486	2655	2020	1915	2445	2500	2122	2122		
at altitude (m)	12192	10973	10973	10973	12192	12192	12192	12192		9144
Mach number	2,343	2,502	1,904	1,805	2,305	2,356	2,00	2,00		1,70
rate of climb at sea level(m/s)		203,2	315,97		330					
Ceiling (m)	17069	19812	18288	15240	17000	1800				
radius of action (km)	362	1270	563	370	750	1500	1093	556		
with warload (kg)							4 Mic			
maximum range (km)	3219	5552	4023	4627	2900	>4000				
DEVELOPMENT										
First flight	21.12.70	27.7.72	2.2.74	18.11.78	6.10.77	20.3.81	4.9.86	4.94	9.12.88	1990
Production	>600	>1286	3835	1146	>600	>200	~330	~600	~300	~384
ARMAMENT										
guns (number x caliber)	1x20	1x20	1x20	1x20	1x30	1x30	1x30	1x27	1x27	1x20
Rockets: no x mm										
Bomb load (kg)		11113	5443	6214			9000			
air-to-air missiles	6 Phoenix	6 Amraam	4 Amraam	4 Amraam	6 Aphid	10 Alamo Archer	8 Mica	6 Amraam	3 Amraam	Amraam
air-to-surface missiles			6 Maverick				2 Exocet		2xRb15	

9.2. Fighter-Bombers

Most fighters are designed for air combat, and later adapted for ground attack, trading agility for payload. Some fighters were designed from the outset for the attack mission, and thus lack a significant air combat capability. They are listed in this section as fighter-bombers.

9.2.1. Seven Generations of Fighter-Bombers

The following photos depict the main types of fighter-bombers, identified by the same seven generations as fighters.

Fighter-Bombers (Generation):

a. Douglas A-1D Skyraider (I)

b. Douglas A-4E Skyhawk (III)

c. Vought A-7B Corsair II (V)

d. Fairchild A-10A Warthog (VI)

e. Lockheed F-117A (VII)

f. Rockwell OV-10A Bronco (IV)

g. Fiat G. 91R3 (II)

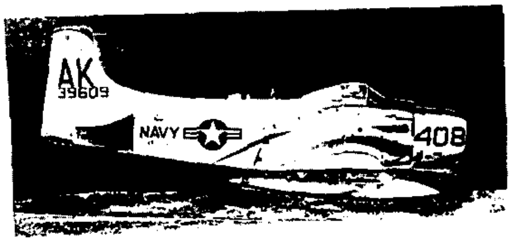
h. Alenia-AerMacchi-Embraer AMX (V)

i. Sukhoi Su-25 Frogfoot-A (VI)

j. Sepecat Jaguar-A (IV)

9.2.2. Specification Tables for Fighter-Bombers

The specifications for fighter bombers are given in the same format as for fighters (9.1.3.).



a

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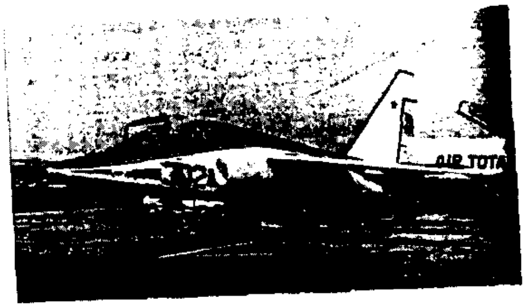

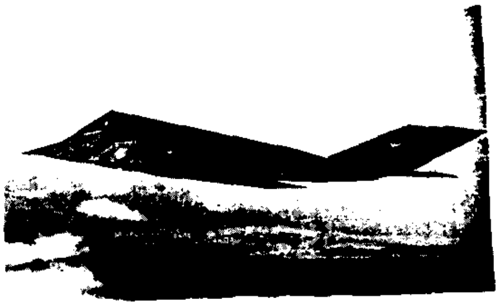

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FIGHTER-BOMBERS: GENERATIONS I - VII

AIRCRAFT	I	II	II	III	IV	IV	V	V	VI	VI	VII
manufacturer	Douglas	Fiat	Soko/Aviane	Douglas	Rockwell	Sepecat	Vought	Alenia	Fairchild	Sukhoi	Lockheed
designation	A-1	G.91R3	Orao	A-4M	OV-10 A	Jaguar	A-7 E	AMX	A-10 A	Su-25	F117 A
name or model	Skyraider		J-22	Skyhawk	Bronco	A	Corsair II		Warthog	Frogfoot	
ENGINE											
manufacturer	Wright	Bristol Siddeley	Rolls Royce	Pratt & Whitney	Air Research	Rolls Royce/Turbomeca	Allison	Rolls Royce	General Electric	Tumansky	General Electric
designation	R-3350-26WA	Orpheus 803	Viper 832-41	J52-P-408	T76-G 416	Ado?-102	TF41-A-2	Spey 807	T34-GE-100	R-195	F404-GE-F102
thrust (kg) without/with afterburning	2700HP	2268	2x1814	5080	2x715 HP	2x2435/3630	6804	5000	2x4112	2x4500	
DIMENSIONS											
Length overall (m)	11,89	10,29	14,90	12,29	12,67	15,52	14,06	13,23	16,26	15,53	20,08
span (m)	15,47	8,56	9,30	8,38	12,19	8,69	11,80	8,88	17,52	14,36	13,20
height overall (m)	4,75	4,03	4,52	4,57	4,62	4,92	4,90	4,55	4,47	4,80	3,78
wing area (m^2)	37,19	16,42	26,00	24,16	27,03	24,00	34,83	21,00	47,01	33,7	105,9
WEIGHTS											
empty (kg)	4790	3100	5500	4899	3161	7000	8668	6700	9761	9500	13608
maximum (kg)	11350	5500	10900	11113	6563	15500	19050	13000	22680	17600	23514
fuel-total (1)											
fuel-internal (1)	1436	1005	3120	3028	976	4500	5678	3500	4853		
fuel-external (1)	3x568	2x520	7x500	3788	871	3x1200	4542	3360			
PERFORMANCE											
Maximum speed (km/h)	584	1075	1130	1040	452	1593	1112	1050	681	975	1040
at altitude (m)	4575	0	0	0	0	10973	0	0	0	0	0
Mach number		0,879	0,925	0,852		1,501	0,911	0,86	0,558	0,799	0,852
rate of climb at sea level (m/s)	14,5	30,48	89,00	52,33	13,47			52,06	30,47		
Ceiling (m)	7740	13106	15000					13000		7000	
radius of action (km)	1206	322	522		367	507	825km+1h	528	1000	1250	1112
with warload (kg)							12x113	2722		4000	2268
maximum range (km)		1851	1320	3225	2298	4210	4604	3336	4091		
DEVELOPMENT											
First flight	18.3.45	9.9.56	31.10.74	21.8.54	16.9.65	19.3.69	27.10.65	15.5.84	10.5.72	22.2.75	12.77
Production	3180	618	416	>800	>250	376	1477	192	713		64
ARMAMENT											
guns (number x caliber)	2x20	2x30	2x23	2x20		2x30	1x20	1x20	1x30	1x30	
Rockets: no x mm											
Bomb load (kg)	3629	680	2800	4170	1633	4536	9072	3800	7250	4400	22268
air-to-air missiles											
air-to-surface missiles							6 Maverick		6 Maverick		

9.3. Bombers

The aircraft designed from the outset as bombers fall under three groups: (i) the light bombers, which have often been superseded by fighter-bombers or ground attack versions of fighters; (ii) the medium bombers, which have in most cases been replaced by interdiction fighters; (iii) the heavy or long-range strategic bombers which cannot be replaced by smaller aircraft.

9.3.1. Five Generations of Bombers

In the period following World War Two, five generations of bombers can be distinguished:

(i) the last propeller-driven long-range bombers;

(ii) the first jet-powered bombers, which were subsonic;

(iii) the supersonic, high-altitude bombers, which were short-lived due to the threat of SAMs;

(iv) the bombers with variable geometry wings, allowing supersonic speed at high altitude, and more important, high-speed low-level penetration;

(v) the stealth bomber.

The main types are listed in Table VIII.

BOMBER GENERATION	**LIGHT**	**MEDIUM**	**HEAVY**
I - Propeller driven			Convair B-36 Tupolev Tu-20 Bear
II - Subsonic-jets	English Electric Canberra Martin B-57 Ilyushin Il-28 Beagle Sud-Aviation 4050 Vautour II Douglas A-3 Skywarrior Douglas B-66 Destroyer Blackburn Buccaneer Grumman A-6 Intruder	Vickers Valiant Handley Page Victor Avro Vulcan Boeing B-47 Stratojet Tupolev Tu-16 Badger	Boeing B-52 Stratofortress Myasischev Mya-4 Bison
III - High altitude supersonic jets		Convair B-58 Hustler Tupolev Tu-22 Blinder Dassault Mirage IV A North American A-5 Vigilante	North American XB-70 Valkyrie Myasischev Bounder
IV - Swing-Wing		General Dynamics F-111 Aardvark Sukhoi Su-26 Fencer Panavia Tornado	Rockwell B-1 Lancer Tupolev Tu-26 Backfire Tupolev Tu-160 Blackjack
V – Stealth			Northrop B-2

Table VIII

Five post-war generations of bombers

9.3.2. Light, Medium and Heavy Bombers

The following photos depict the main types of bombers:

Light Bombers

a. English Electric Canberra B.8
b. Martin RB-57D
c. Ilyushin Il-28
d. Sud-Ouest 4050 Vautour II-B
e. Douglas A-3B Skywarrior
f. Blackburn Buccaneer B.1
g. Grumman A-6E Intruder

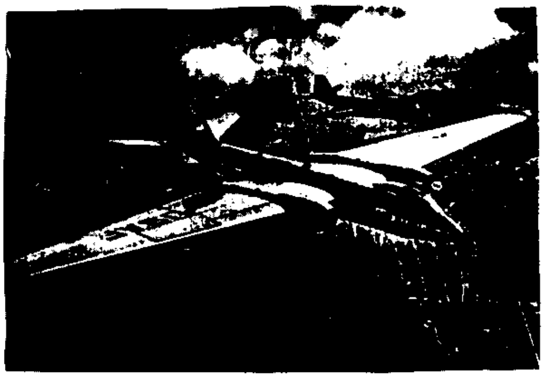
Medium Bombers

h. Vickers Valiant B.1
i. Handley Page Victor B.1
j. Avro Vulcan B.2
k. Boeing B-47E Stratojet
l. Tupolev Tu-16 Badger G with "Kingfish" missile
m. Convair B-58A Hustler with external pod
n. *Tupolev Tu-22 Blinder A*
o. Dassault Mirage IVA
p. North American A-5A Vigilante

Heavy Bombers

q. Convair B-36F as mother-plane with F-84 fighter escort
r. Tupolev Tu-20 Bear B with "Kangaroo" missile
s. Northrop XB-49
t. *Boeing B-52H Stratofortress with 2 Hound Dog missiles*
u. Myasischev Mya-4 Bison
v. Myasischev Bounder
w. North American XB-70 Valkyrie
x. Rockwell B-1 Lancer
y. Tupolev Tu-26 Backfire
z. Tupolev Tu-160 Blackjack
z'. Northrop B-2 Spirit

a



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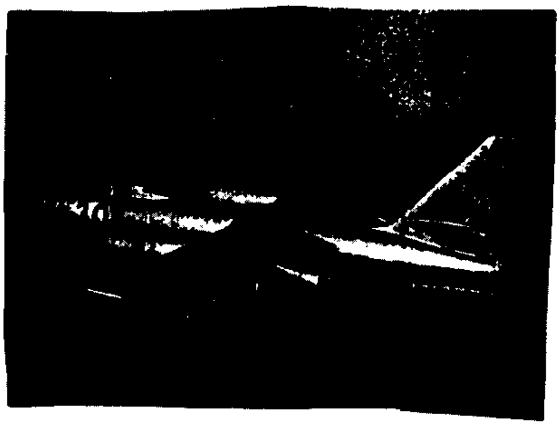

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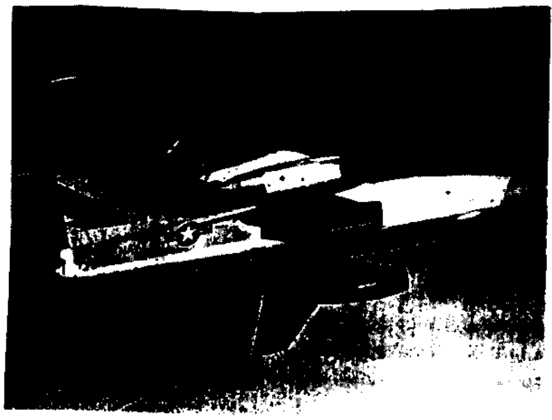

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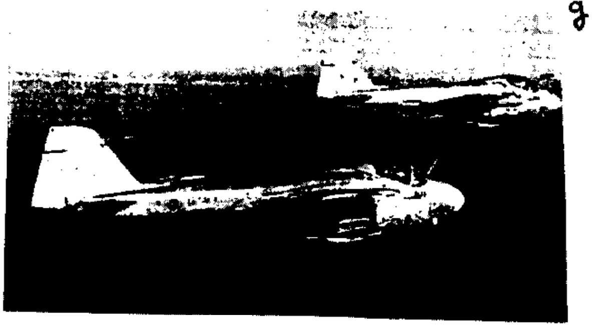

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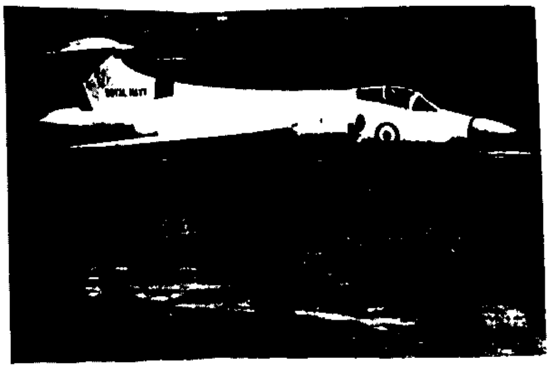

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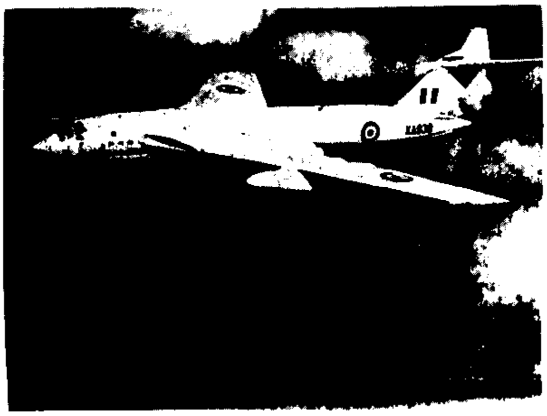

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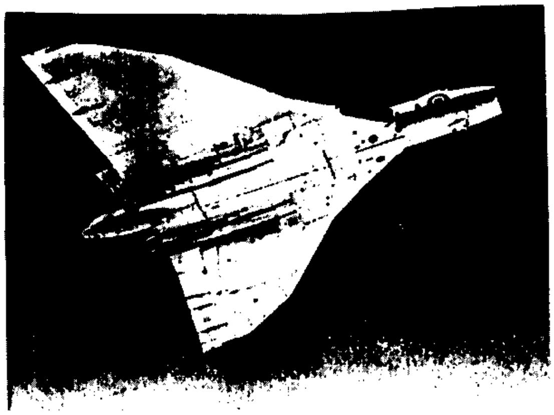

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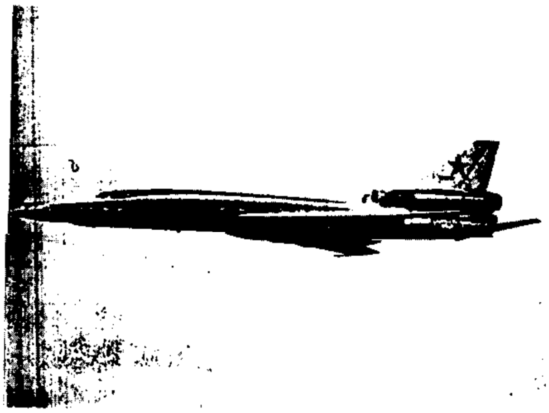

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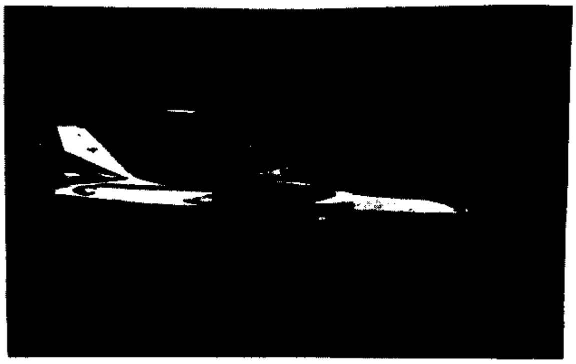

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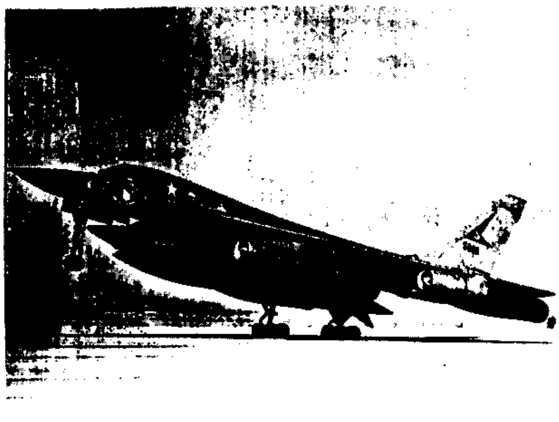

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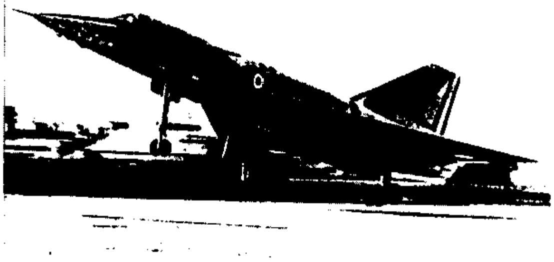

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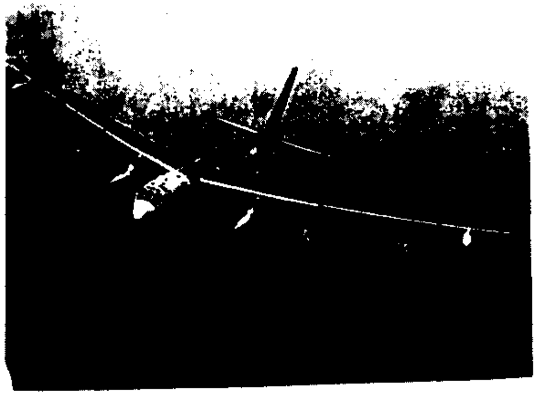
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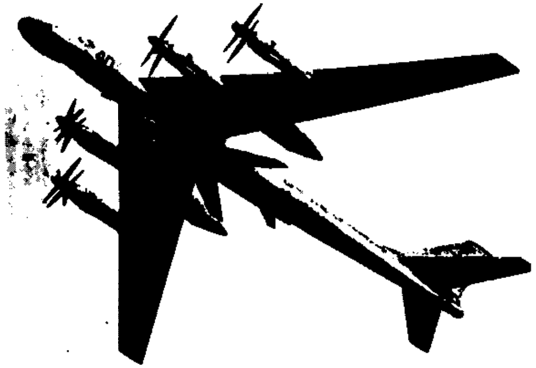
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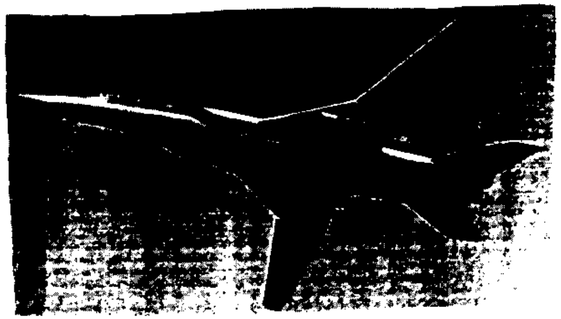
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9.3.3. Specification Tables for Bombers

The specification tables, on the following pages, are presented in the same format for fighters (9.1.3.), fighter-bombers (9.2.3.) and bombers (9.3.3.).

LIGHT BOMBERS

AIRCRAFT								
manufacturer	English Electric	Martin	Ilyushin	Sud-Ouest	Douglas	Douglas	Blackburn	Grumman
designation	Canberra	RB-57C	IL-28	4050	A-3B	RB-66B	Bucaneer	A-6E
name or model	B (1)MK-8		Beagle	Vautour II-A	Skywarrior	Destroyer	S.MK.2	Intruder
ENGINE								
manufacturer	Rolls Royce	Wright	Klimov	Snecma	Pratt & Whitney	Allison	Rolls Royce	Pratt & Whitney
designation	Avon 109	J65-W-5	VK-1	Atar 101 E-3	J57-P-G	J79-A-13	Spey 101	J52-P.408
thrust (kg) without/with afterburning	2x3557	2x3275	2x2699	2x3501	2x4400	2x5262	2x5003	2x4218
DIMENSIONS								
length overall (m)	19,96	20,67	18,90	15,57	23,27	22,89	19,39	16,69
span (m)	19,51	32,77	20,78	15,09	22,10	22,10	12,90	16,15
height overall (m)	4,77	4,77	6,70	5,50	6,95	7,19	5,03	4,93
wing area (m^2)	89,19	89,19	50,0	45,0	75,4	72,5	47,26	49,14
WEIGHTS								
empty (kg)	10511		12428	10500	17373	18002		12525
maximum (kg)	24925	24998	19958	18000	37195	35834	24494	27397
fuel-total (1)								
fuel-internal (1)	30351				16683	17592	6820	8873
fuel-external (1)	2x1109		2x909			2x1705	2x1136	5x1514
PERFORMANCE								
maximum speed (km/h)	827	937	937	1015	901	956	1130	1037
at altitude (m)	0	12192	4572		10173	10973	0	0
mach number	0,68	0,908	0,806		0,848	0,899	0,92	1,06
rate of climb at sea level (m/s)	17,3	17,8	17,8	60	10,2	11,0	76,2	38,7
ceiling (m)	14630	21336	12498	15000	12497	13716		12925
radius of action (km)	644	1851	1102-1368		1690	1288	970	813
with warload (kg)								
maximum range (km)	5840	4265	3540	2418	4667	3058	3220	5222
DEVELOPMENT								
first flight	13.4.1949	20.8.1953	1947	15.3.1951	31.3.1949	28.7.1954	30.4.1958	19.4.1960
production	1001	403	>1000		283	209	140	708
ARMAMENT								
guns (no. x caliber in mm)	4x20 Hispano		4x23	4x30	2x20	2x20		
rockets (number x caliber)	16x114						Martel	Harm
bomb load (kg)	2722	reconnaissance	2000		5443	reconnaissance	3629	8165
air-to-air missiles								
air-to-surface missiles							2 Martel	

* With 15m high obstacle

MEDIUM BOMBERS

AIRCRAFT									
manufacturer	Vickers	Handley-Page	Avro	Boeing	Tupolev	Tupolev	Convair	North American	Dassault
designation	Valiant	Victor	Vulcan	B-47 E	Tu-16	Tu-22	B-58 A	A-5 A	Mirage
name or model	B.MK.1	B.MK.2	B.MK.2	Stratojet	Badger	Blinder	Hustler	Vigilante	IV A
ENGINE									
manufacturer	Rolls Royce	Rolls Royce	Bristol Siddeley	General Electric	Mikulin	Koliesov	General Electric	General Electric	Snecma
designation	Avon 201	Conway 201	Olympus 301	J47-GE-25	AM-3 M	VD-/ M	J79-GE-5B	J79-GE-8	Atar 9K
thrust (kg) without/with afterburning	4x4536	4x9344	4x9072	6x2722	2x9500	2x16000	4x7676	2x7711	2x7000
DIMENSIONS									
length overall (m)	33,00	35,03	30,45	34,34	36,9	42,60	29,49	22,41	23,50
span (m)	34,85	36,58	33,83	35,36	33,5	23,50	17,32	16,15	12,00
height overall (m)	9,80	9,18	8,28	8,51	10,8	10,00	9,58	5,91	5,40
wing area (m²)	218,9	241,3	368,8	132,7	169	162,0	143,3	65,0	78
WEIGHTS									
empty (kg)	34419			36630					14500
maximum (kg)	79379	90100	91700	99790	75750	92000	73900		31600
fuel-total (1)									
fuel-internal (1)	45332			41824	45450	42500	60550	28123	14000
fuel-external (1)				2x6728				2x1514	2x2500
inside bombs compartment	14684								
PERFORMANCE									
maximum speed (km/h)									
at altitude (m)	892/10473	1010/10973	1040/12192	1014/3048	998/3048	1610/12192	2229/13411	2229/12192	2340/12192
mach number	0,839	0,95	0,98	0,858	0,843	1,52	2,10	2,10	2,20
rate of climb at sea level (m/s)	20,3			23,7					
ceiling (m)	16459	16290	19812	13716	11582	13300	16764	21336	19995
radius of action (km)	2626.3621	2748	2736	2414	2012	1300-2200	1930	1770	1995
with warload (kg)									
maximum range (km)	5252-7242	7400-9660	7644	6437	4500	5660	3220-4020	4830	4000
DEVELOPMENT									
first flight	8.5.1951	1.2.1956	6.10.1950	17.12.1947	~1954	~1961	11.11.1956	31.8.1958	17.7.1959
production	104		>101	2291	>500	250	116	>100	62
ARMAMENT									
guns (no. x caliber in mm)				2x20 M-24 A1	3x23		1x20 M61		
rockets (no. x caliber)									
bomb load (kg)	9536	15876	9526	9072	9072	12000			
air-to-air missiles									
air-to-surface missiles		1 Blue Steel	1 Blue Steel		1 Kipper	1 Kitchen		4 Bullpup	1 ASMP

* With 15m high obstacle.

HEAVY BOMBERS

AIRCRAFT											
manufacturer	Convair	Tupolev	Boeing	Myasischev	Myasischev	North American	Tupolev	Tupolev	Northrop	Rockwell	Northrop
designation	B-36J	Tu-20	B-52G	MYA-4		XB-70A	Tu-26	Tu-20M	YB-49	B-1B	B-2
name or model		Bear-H	Stratofortress	Bison	Bounder	Valkyrie	Backfire-C	Blackjack	-	Lancer	-
ENGINE											
manufacturer	Pratt & Whitney	Kuznetsov	Pratt & Whitney	Mikulin	Soloviev	General Electric	Kuznetsov	Samara	Allison	General Electric	General Electric
designation	R-4360-53	NK-12 MV	J57-P-43W	AM-3M	D-15	J93-GE-5	NK-25	NK-321	J35-A-5	J101-102	F118-110
thrust (kg) without/with afterburning	4x3800 HP*	4x14795 HP	8x6237	4x8700	4x12990	6x14600	2x25000	4x25000	8x1814	4x7710-15208	4x8281
DIMENSIONS											
Length overall (m)	49,40	49,50	48,02	49,5	62,5	56,79	42,46	54,10	16,40	23,84-41,67*	21,03
span (m)	70,10	51,10	56,39	51,9	40,2	32,00	23,30-34,28**	35,60-55,70**	52,43	43,68	52,43
height overall (m)	14,22	12,12	12,40	15,2		9,14	11,5	13,10	6,35	10,24	5,18
wing area (m^2)	443,32	311,1	371,6	340		585,3	175,8-?**		371,60	181,20	>464,5
WEIGHTS											
empty (kg)	77580	120000	78000						39960	87090	100000-110000
maximum (kg)	185973	188000	219353	160000	181400	240400	124000	275000	96617	216364	170550
fuel-total (1)											81650-90720
fuel-internal (1)		95000	124923								
fuel-external (1)			2x3650				50000				
bombs									13608	34020	22680
PERFORMANCE											
Maximum speed (km/h)	661/11095	815/7620	988/12192	1000/3048	1590/11292	3186/21336	2000/12192	2000	853	1205	915
at altitude (m)									0	152	0
minimum speed	629	711	853	840/12192	960/10673		900	800			
Mach number			0,93	0,84	1,50	3,0	1,88	1,88			
rate of climb at sea level (m/s)			12,7						27,9		
Ceiling (m)	13700	12000	17983	13716			13300	18300			15240
reach (km)									5564	12000	11675-12231***
speed (km/h)									615		
altitude									10668-12192		
radius of action (km)	5450	6400		2414	7350		1500				
with warload (kg)	4536	11340		18144			2200				
maximum range (km)			14484	9656	4830-6440	12230 (M.30)	2000/1300	12000			
DEVELOPMENT											
First flight	8.9.1945	1952	2.10.1952	1955-6	1959	21.9.64	~1971		21.10.47	18.10.84	17.8.89
Production	328	>200	748	~200	prototype	2 prototypes	~200	~30	2	100	20 (1999)
ARMAMENT											
guns (number x caliber)	16x20/1x37		4x12.7	10x23	1x23						
Rockets: no x mm											
Bomb load (kg)	38100	>11340	27442	18144			24000	36000		56700	18144
air-to-air missiles											
air-to-surface missiles		16 ALCMS	20 ALCMS		Kangaroo		10 ALCMS	12 ALCMS		20 ALCMS	16 ALCMS

* Plus 4 General Electric J47-GE-19 of 2536Kg ** Swing-wing *** With 16919-10886 Kg of weapons