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Designing for Stealth in Fighter Aircraft (Stealth from the Aircraft Designer's Viewpoint)

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ABSTRACT

The reduction or other control of an aircraft's radar, infrared, visual and acoustic signatures can greatly improve its survival, resulting in improved weapons' effectiveness. Although radar stealth is important, it is pointless without low observability in the other regions of the electromagnetic spectrum. However, this paper, for reasons of brevity will concentrate on methods to control radar signature only. The topics of: benefits of signature control; contributions of an aircraft to its radar cross section (RCS); methods to reduce RCS; penalties/costs of RCS-reduction, in terms of performance, volume, weight and maintenance; use of radar absorbing and structural composite materials are addressed. The conclusion is that while signature control is important, there *are* penalties to be paid. RCS-reduction has become merely another factor to be considered in the series of compromises made during aircraft design trade-offs.

INTRODUCTION

Why signature control? The control of signatures allows aircraft to achieve higher exchange ratios and improved survivability, thus allowing the destruction of highly protected targets without unacceptable loss. While remaining undetected gains time to plan and execute the optimum attack, once combat is engaged it will be difficult to remain unseen. Once launched, a missile in flight, unless itself is stealthy, will soon be detected by its target, and the launch aircraft, manoeuvring for another attack or to escape retaliation, will become distinctly less stealthy. Although stealth offers significant benefits for beyond-visual-range (BVR) combat, close combat is still probably inevitable. Any benefit is likely to be limited to the increased effectiveness of countermeasures that will not have to disguise a large radar or infrared signature but rather, decoy the threat. For the ground strike role, the great benefit of stealth, other than survivability, is that it gives the attackers the element of surprise. This lets the pilot concentrate on hitting the target, rather than jinking and diving to avoid enemy fire. One of the lessons learned in Vietnam was that AAA fire is an important threat. It is probably the primary threat for stealthy attack aircraft. It was a lesson partially forgotten by the time of the 1990-91 Gulf War. In addition, Western political and public opinion has become less tolerant of loss of life on its own side.

RADAR SIGNATURE CONTROL IN PRINCIPLE

The threat to aircraft of detection and tracking comes from a variety of sources. Table 1 indicates typical radar threats and their characteristics.

Radar System	Frequency (GHz)	Wavelength (in)
Early warning	0.15-0.2	70-80
	3-4	3-4
Ground control intercept	2-3	3-5
Height finders	2-7	1-5
Aircraft	8-12	1-1.5
Air-to-Air missiles	9	1
SAM transportable		
Acquisition	0.15-3	3-70
Tracking	5-10	1-2
SAM mobile		
Acquisition	2-6	2-5
Tracking	5-13	1-2
Radar guided AAA	14-16	0.6-0.7

Table 1 Radar Threats [1]

The radar range equation [2] can be expressed as:

$$R = \left[\frac{PA^2\sigma}{4\pi\lambda^2 N}\right]^{\frac{1}{4}}$$

Since the radar range is a function of the fourth root of the radar cross section (RCS) an order of magnitude reduction in RCS, for example, will give a 44% reduction in range:

$$\frac{R_1}{R_2} = \left[\frac{\sigma_1}{\sigma_2}\right]^{\frac{1}{4}} = \left[\frac{1}{10}\right]^{\frac{1}{4}} = 0.56$$

Similarly the search area of the radar will be reduced to 32% and search volume to 18%. A large reduction in RCS is therefore essential to have a significant effect.

Radar signature control methods depend critically on the size of the electrically-conducting component being illuminated compared with the wavelength of the radar signal illuminating it. If the wavelength of the signal is much less than the physical size of the component, and if the component is smooth enough, it will reflect radar waves much as a mirror reflects light.

CONTRIBUTIONS TO RCS FOR A CONVENTIONAL AIRCRAFT

RCS depends on: aircraft shape, aspect angle or orientation with respect to radar line of sight (LOS), ratio of radar wavelength to target size, polarisation of transmit and receive antennae, surface quality of the target, and constitution of the target.

The RCS of an aircraft is determined by the magnitudes of two distinctly different contributions:
(a) Its size and shape, both overall and in detail.
(b) The electromagnetic properties of the airframe materials.

Aircraft shaping is useful over a wide range of radar frequencies but over a limited range of aspect angles. Typically, for fighter aircraft, a forward cone of angles is of greatest interest and hence, large returns can be shifted out of this sector into the broadside directions. The aircraft can be shaped to ensure that most radar waves will be scattered and not reflected back to the transmitter. Leading and trailing edges of wings, control surfaces, inlet lips, door gaps, etc., can be aligned to ensure that the energy that is, unavoidably, reflected back to the transmitter is concentrated into a few spikes. This will give the opposing radar one good return when the alignment is ideal, but a much weaker return on subsequent sweeps.

MAJOR CONTRIBUTORS TO RCS FOR A CONVENTIONAL AIRCRAFT

Engine compressor faces (forward) and turbines (aft) due to Doppler signature.
Air inlets for engines.
External stores, including missiles seeker heads.
Wing leading edge, especially if unswept.
Corner reflections at intersections of horizontal and vertical tails.
Wing from directly below/above.
Radome and bulkhead, if transparent to illuminating radar.
Cockpit, including cavity effect due to a very large number of corner reflectors.
Engine nozzle if viewed from rear.
Flat, slab-sided fuselage when viewed from side.

SMALLER CONTRIBUTORS TO RCS FOR A CONVENTIONAL AIRCRAFT

Fuselage in head on view.
Wing leading edge and control surface gaps which cause scattering.
Local air inlets e.g. for cooling and air conditioning.
Local surface protuberances. Even the smallest protuberances cannot be ignored and each may become resonant at a different frequency.
Long thin fairings including missiles.
Vertical and horizontal tails.

METHODS TO REDUCE RCS OF AN AIRCRAFT

There are different approaches to shaping an aircraft to reduce its RCS
(a) Using a compact, smoothly blended external geometry to achieve a continuously varying curvature (e.g. SR-71 and B-2).
(b) Using a faceted configuration, with flat surfaces to minimise normal reflections back to the illuminating radar (e.g. F-117, DASA Firefly [3] {Fig 1}).

Many considerations govern which of the above methods is used. These include: the aspect of the aircraft most considered to be operationally important, the ease of manufacture and the use of radar absorbing materials (RAM) referred to later.

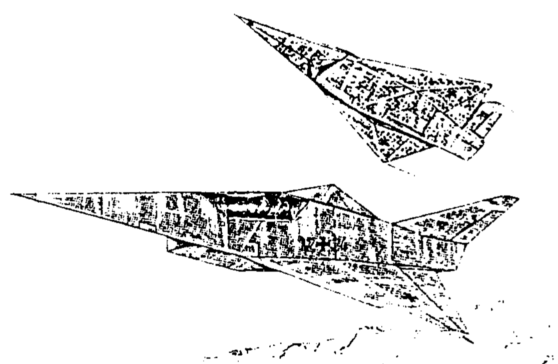

Figure 1 The DASA Firefly project ran from 1981-87 by MBB under a contract from the German Air Force. The work led to the eventual development of a 3/4 scale piloted wind tunnel model of a multi-faceted aircraft. Project was claimed to have very probably a lower RCS than the F-117, despite having half the number of facets [3].

SUMMARY OF RCS REDUCING TECHNIQUES [2,4]

Reduce the number of radar spikes by concentrating on as many similarly aligned reflecting surfaces the extreme example being the YF-23. Similarly, all of the panels on the underside of the F-117 are hexagonal in shape. Every line on the underside was thus parallel to the trailing edge of the wing, which ensured that any return from a door would be swamped by the minimal signature of the wing. A similar approach was adopted for the F-22 (Fig 2).

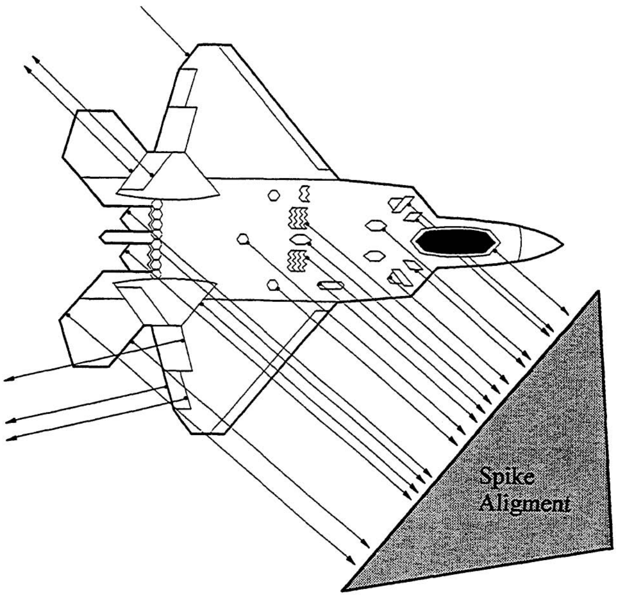

Figure 2 Alignment of surfaces on F-22 to reduce number of strong radar spikes

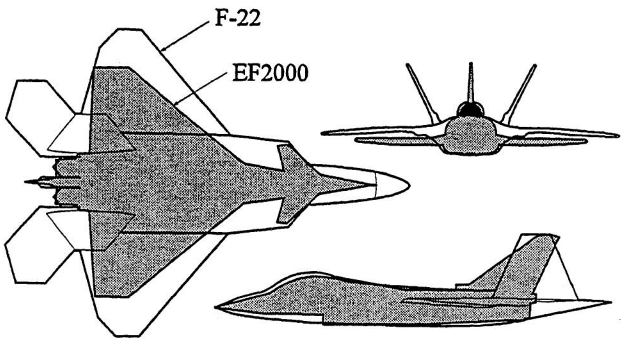

Figure 3 Size and configuration comparison between EF2000 and F-22. Small physical size is an advantage and both EF2000 and Rafale are considerable smaller than the F-22 with 35% less wing area and with their delta wings both European designs offer large fuel volume for their size. The EF2000 was probably the first western European aircraft to have target levels of RCS in its specification. Eurofighter's EF2000 has a contractual value of RCS for front hemisphere with a configuration of 4 AMRAAMs semi-recessed and two pylon-mounted SRAAMs [16].

Minimise aircraft size (Fig 3), this is valuable in addition to reducing RCS.

Use swept leading edges (but excessively swept wings can produce performance, stability and control problems).

Avoid vertical surfaces altogether but if not feasible, cant the surfaces to avoid right angle corner reflectors.

Carry stores, including fuel, internally.

Minimise or eliminate control surfaces (e.g. F-117 and YF-23 use ruddervators, F-22 has dispensed with a dedicated speedbrake).

Eliminate the cockpit transparency cavity by employing an unmanned vehicle or reduce cavity effects by treating the transparency with a thin conducting layer (e.g. F-16).

Use a clean external geometry with minimum protuberances (aerials, inlets, doors, gaps).

Avoid flat or re-entrant surfaces likely to be normal to incident radiation.

Bury engines with air inlets and exhausts located over the upper surface of the airframe, to mask the cavity from the major, ground-based illuminating radar threat (e.g. B-2, F-117).

Give the inlet duct an 'S' shape to hide the compressor face and to force multiple reflections on the RAM-lined diffuser duct (Figs 4 & 5).

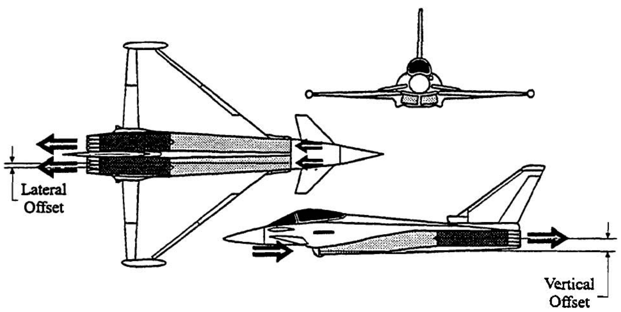

Figure 4 Use of S-shaped subsonic inlet diffuser duct on the EF2000. The inlet offset, predominantly vertical in this case, provides fuselage shielding to reduce inlet AoA at high aircraft AoA. Both methods when combined with RAM lining reduce the RCS by producing 100% line-of-sight blockage to engine compressor face. The engine face of the EAP technology demonstrator could be seen by looking down the inlet. This is not the case, as shown, for the EF2000.

Screen the inlet, use gauzes, vanes and deflectors within the diffuser duct. Extend length of inlet guide vanes and arrange them to cause internal reflections on RAM and mask the cavity. On supersonic aircraft such screens, etc., can only be placed within the subsonic duct, otherwise unacceptable pressure recovery losses occur.

Avoid variable geometry inlets to minimise reflections from the gaps and steps of the compression ramps and eliminate bypass doors.

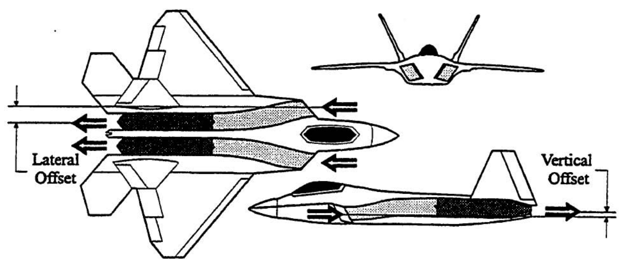

Figure 5 Lateral offset of the inlets is predominantly used on the F-22 to hide the compressor face and to clear the aircraft's large internal weapons bays.

Carefully shape the inlet lips (e.g. chevrons or sweep to align with major surfaces).

Inlet boundary layer diverter flows should bleed around engine cavity or into bypass duct and not be dumped overboard (via doors) separate to nozzle flow.

Design and manufacture any internal structure within radar-transparent skins to reduce reflections in given directions (e.g. the sloping radar bulkhead on the F-22). The cumulative effect of the interior reflections could easily exceed the radar return from a metallic skin.

Use (RAM) wherever appropriate (e.g. leading edges, bulkhead and black boxes within radar cavity, on the interior the inlet and on metallic structure under radar-transparent skins).

Use a very high quality of manufacture to avoid gaps, holes, etc.

Avoid discontinuities in conducting paths since electromagnetic waves induce currents in aircraft skin.

Cover gun port, inlet and exhaust of APU when not in use

If a radar is to be carried, use low probability-of-intercept/detection type, the features and use of which can be tailored according to the mission. The philosophy is to use a flexible combination of power, frequency, waveform and pulse repetition frequency to produce elusive signals, rather than to suppress radiated power as an end in itself.

THE COSTS OF SIGNATURE CONTROL

The requirement for aircraft to be stealthy results in unconventional configurations, the producability, performance controllability and maintainability of which contain a large number of unknowns. However, the overriding requirement for any future aircraft is affordability. This affects the availability of aircraft (number of aircraft to perform a mission is a function of aircraft in fleet), as well as reliability, maintainability and survivability.

The probability of a kill [5] :

$$P_K = P_D \times P_{A/D} \times P_{H/A} \times P_{H/K}$$

Where P_D = Probability of detection

$P_{A/D}$ = Probability of acquisition given detection

$P_{H/A}$ = Probability of a hit given acquisition

$P_{K/H}$ = Probability of a kill given a hit

Thus RCS reduction plays only a part, albeit a major one, in kill probability.

History shows that it is easy to turn a good idea into an unaffordable one. The F-22 is a solution to the problem but probably is unaffordable by all except the United States. Some of the adverse effects of RCS reduction are: increased costs, additional maintenance, and added weight and volume leading to performance penalties. In addition, stealth brings with it 'special access' security which is costly in terms of both time and money and if applied without careful thought, can become an impediment. The A-12 security was so tight that the US Navy and DoD did not subject the programme to normal reviews and were late in learning of weight, schedule and cost problems [6] . Using admittedly **very uncertain estimates** [7] of flyaway cost, the cost per empty weight seems remarkably similar for modern fighter/strike aircraft. For example the figure for the F-22 is $2,840/lb ($92,400,000 for 32,500lb based on 442 aircraft [8]), for the Royal Air Force's EF2000 the figure is $2,450/lb ($52,8000,000 for 21,500lb based on 250 aircraft) and that for the Rafale is $2,920/lb ($58,300,000 for 19,970lb based on 320 aircraft). Yet, when the penalties of signature control are considered (below), the much larger and 'gold-plated' stealthy F-22 is reputedly [8] around 1.75 times more expensive than the 'chrome-plated' less stealthy EF2000. That the F-22 is a large aircraft must hardly come as a surprise because to get a very low RCS, the fuel and weapons need to be carried internally. Nevertheless it has to be borne in mind that US fighters have traditionally been larger than European designs, because of their longer range requirement.

PERFORMANCE PENALTIES

The aerodynamic problems posed by stealthy aircraft, especially if they are inherently unstable, are:

(1) Stability and control due to reduction/removal of control surfaces and the limited area of control surfaces all ensuing from stealth considerations. The need for tailless designs places a great deal of emphasis on the flight control system (FCS) and may require thrust vector control to downsize the vertical tails. Currently the F-22's two-dimensional exhaust nozzle, used for signature reasons, is around 20% heavier and more expensive than an equivalent 3-D one.

(2) The effect of controllability of novel configurations (e.g. the YF-23 which employed highly tapered and aerodynamically-loaded wing tips which classical aerodynamicists would regard as undesirable), and the associated effect on the FCS (i.e. increased mass and power offtake penalties) and the impact on the FCS of the air data system, the efficacy of which may also be reduced by stealth considerations.

(3) The effect on aircraft and engine performance of inlet duct positioning and shaping, due to stealth requirements. The loss of available installed thrust due to air inlet and nozzle shaping for IR and RCS control can be a major penalty. The insistence of 100% LOS blockage to the engine face to reduce RCS, with the engine face offset 0.7 to 1.2 diameters from that of the inlet throat, will via a long S-duct, mean losses in stagnation pressure recovery that increase markedly with throat Mach number (Fig 6 [9]).

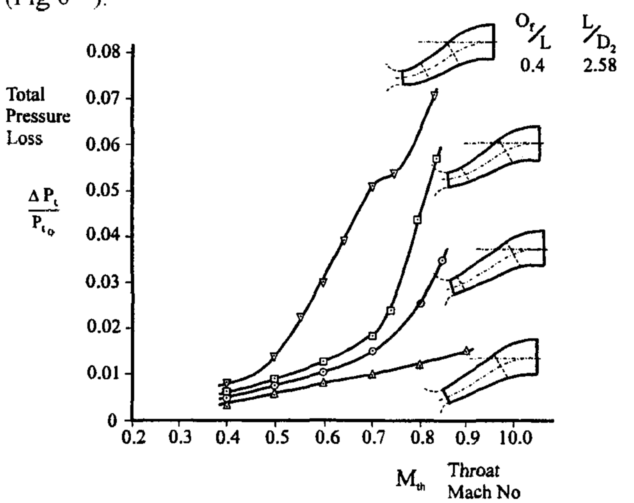

Figure 6 Basic inlet duct loss for S-bend duct due to changes in first bend shape [9].

Large vertical offset can lead to trim drag penalties due to the high thrust lines but as shown in Fig 3 the EF2000 appears to have 100% LOS blockage and achieves this with an inlet/engine arrangement reminiscent of the F-16. The air induction system can be simplified by using a fixed geometry inlet, although its aerodynamic performance (in terms of stagnation pressure recovery) will be severely degraded at high Mach (Fig 7 [10]). The spectrum of angle of attack and sideslip required of the inlet together with the extreme range of hot and cold day operation leads to special needs for matching inlet and engine airflows. This has been done, in the past, quite successfully by variation of the geometry of the compression surfaces and by spilling air from the subsonic diffuser. If the inlet is fixed the former method is not available, which necessitates either direct spill to the freestream via bleed doors or by bypassing air around the engine. The former method is undesirable for RCS

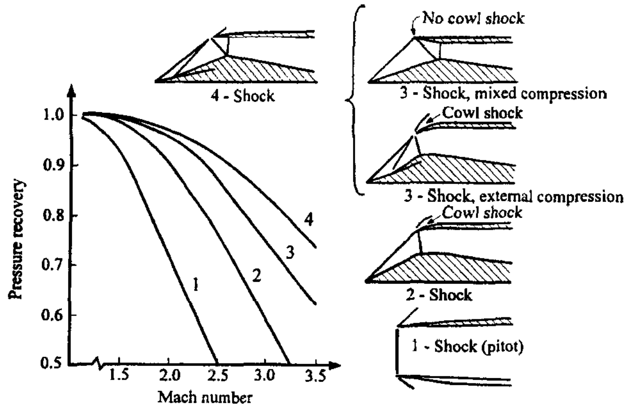

Figure 7 Various types of inlet geometry and their effect on stagnation pressure recovery. The figure shows the 'on-design' case only. Lack of variable geometry would cause losses in pressure recovery at other Mach numbers and AoA [10].

reasons, whereas the latter may benefit cooling of the exhaust, as appears to be the case of the B-2 [11]. Inlets which have to operate at much higher AoA than hitherto are likely to suffer severe flow distortion unless, as on the previous generation of fighters, the inlet is shielded by the fuselage/wing strake or has extensive stagger or have rotating inlet lips (e.g. EF2000). The YF-22's inlet which avoided the use of any variable geometry (to reduce RCS) or shielding, apart from about 30° of stagger, may appear to have been a recipe for disaster but the writer is unaware of any problems during its flight test programme.

In addition, the provision of RCS-reducing screens, vanes or deflectors within the subsonic portion of the inlet duct will further reduce pressure recovery and add weight. However, there may be a need for vortex generators within the duct to suppress flow separation in a fixed inlet at high AoA, for example, and RAM-coating them may serve a dual purpose. The ability to supercruise will not only stretch combat radius but forces an adversary to expend his own fuel in order to get his aircraft to an energy state where he can engage it. Good pressure recovery is vital in the anticipated Mach 1.4-1.6 supercruise regime. Lack of it will degrade the installed thrust and will lead to the need for significantly higher aircraft uninstalled thrust/weight ratios. However, elimination of the actuation hardware (e.g. hydraulics and seals) and movable surfaces (and their inevitable gaps) typically found in a variable geometry inlet will increase reliability while decreasing weight and cost, as well as RCS. Moreover, the volumetric and structural efficiency of the inlet will be improved as a result of fixing the inlet and help pay for the weight of any RAM treatment. It may be that the inlet aperture can have a 3-D geometry. Such shapes offer better aerodynamic performance but have been avoided because their behaviour was difficult to accurately predict. In addition, manufacturing processes have favoured conical or 2-D inlets because of their relative simplicity. However, advances in analysis techniques now allow fixed 3-D shapes to be aerodynamically, electromagnetically and structurally integral with the airframe (e.g. Dassault Rafale). Normally a high cost, heavy item, new production methods may make them more affordable and structural RAM in certain sections of the inlet duct may be a way of reducing weight.

(4) The effect of novel configurations on drag (due to the increased size from the need to carry all stores and fuel internally), buffet and ride quality (due, for example, to very short-coupled configurations) Fig 8.

(5) The problems of weapon release and weapon bay aerodynamic loading caused by internal carriage of stores.

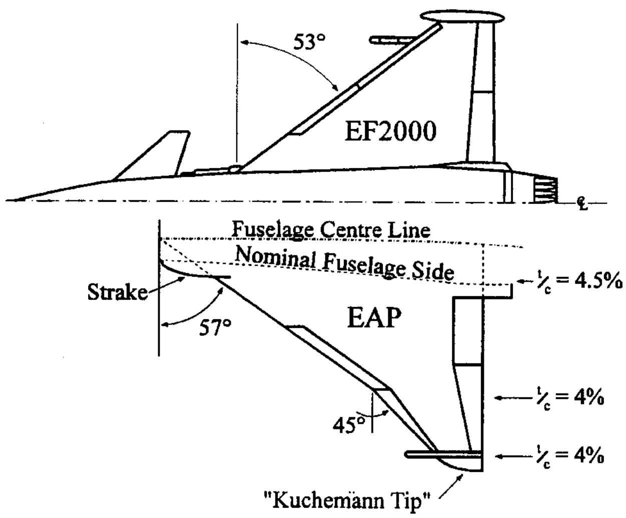

Figure 8 The Experimental Aircraft Programme (EAP) technology demonstrator was used by British Aerospace to explore many of the aerodynamic and signature features (among others) for EF2000. Comparison of wing planforms of the EAP and EF2000 show the kinked leading edge of the former and the straight leading edge and DASS pod of the EF2000. The kinked leading edge on the EAP wing was used to give some extra aspect ratio (and lower span loading) for high subsonic and sustained turn rates for a given wing area [33]. For the EF2000 the RCS properties were optimised but not carried to extremes, hence the EF2000's leading edge is straight.

VOLUME PENALTIES

Fighters are notoriously short of fuel and volume constraints due to internal weapons carriage do not help in this regard. Such large internal weapon bays, their influence on the aircraft structural performance, their effects on stealth characteristics and their operation in weapon release, all contain significant unknowns. However, the USAF has had experience, since the 1950s, with such bays on, for example, the F-102 and F-106.

Nevertheless, the question arises as to whether very low observable (VLO) strike aircraft will be able to carry enough stand-off weapons in their internal bays to achieve a sufficiently high hit rate per sortie. This may be achieved by the use of a very accurate (using GPS) 1,000lb bomb, designed to be as capable as current 2,000lb weapons, (though this argument is equally applicable to 'conventional' weapons carriage). As an example, the F-22 weapons bay had to be redesigned to contain four of the Joint Direct Attack Munition (JDAM-GBU-29) of 1,000lb each, as an alternative to six AIM-120C compressed-carriage AMRAAMs. The F-22's two main weapon bays are each about 2ft deep by 4ft wide by 13ft long with the two cheek bays about 1.7ft wide and deep and 11ft long. This gives a total volume of around 270ft^3, which, allowing for airframe structure and systems, gives enough for perhaps 11,000lb of fuel, sufficient for more than two hours flying. This quantity of fuel is a little under twice that carried internally by an F-16 or equal to that carried internally by an F-15A. Of relevance is that the USAF has the option of putting a fuselage plug in the F-22 to give it longer range and the ability to carry six JDAM internally. In addition a conformal pod that could carry both air-to-air and air-to-ground weapons was reportedly [12] tested during the YF-22's DEM/VAL phase.

WEIGHT PENALTIES

An aircraft that carries all stores and fuel internally requires a large fuselage which, being a major and therefore heavy component, leads to increased weight. For example the operational empty weight of the F-15E (31,700lb) is almost 8% greater than that of the F-15D (29,400lb). While a large measure of this weight increase was due to the structural redesign for the strike role of the F-15E the provision of the extra conformal fuel tankage was a contributor. In 1994 it was realised, from use with the enhanced F-117 RCS prediction tools, that the F-22 had problems with its RCS. This required modification of some aircraft details and increased use of low observability materials, including the inlet duct. The subsonic portion of the F-22's inlet duct appears to be about the same length as that on the F-15. Unspecified signature control changes added 140lb plus 100lb due to due to the use of titanium wing spars. By the time of its critical design review in Feb. 1995 [13] the empty weight of the F-22 had increased by 4% (1,300lb to 32,143lb), only partly due to signature control. The chevrons or sawteeth of the landing gear and weapon bay doors, have been reduced by 60-70% from 6-7 teeth per door to 2 and made bigger and longer. The bigger teeth require additional structure bracing that adds weight, but the bigger teeth mean fewer corners giving smaller RCS [14]. Instead of spending huge amounts of money to correct the performance shortfalls due to the weight growth and engine efficiency shortfalls, the US Air Force decided to accept them and make small adjustments to the aircraft's performance specification. As a result the F-22's sustained turn performance at altitude was relaxed and the g level was lowered a few tenths of a g [13].

MANUFACTURING PENALTIES

Where designing for affordability is concerned, the foregoing performance requirements, and others associated with the smoothness of aerodynamic profile required for stealth reasons, are in fact forces driving away rather than towards affordability targets. There is therefore a very real challenge in achieving an affordable airframe against this background of greater accuracy of build, new materials and new structural forms. For example, the wing span of the B-2 [15] of 172ft is held within 0.25in (0.015%).

With new higher-than-estimated values of its RCS, the F-22 required removing more than half the corners from landing gear and weapon bay doors, reducing access panels by one third and eliminating 80% (200 to 44) of the drain holes on the aircraft undersurface. Ensuring the F-22's RCS remains low is a process of taking care of many thousands of small details, including changes to seams, corners, holes, steps, gaps and edges. The inlet's interior geometry needed changing along with some materials. The tightening of tolerances in manufacture tooling was also required [14].

MAINTENANCE PENALTIES

The application of signature control technology will affect an aircraft's support system. The use of RAM, for example, in structures and as coatings needs extra support, test and evaluation procedures to verify the continued performance of the signature reduction methods. In 1995 the inspection time for the B-2 was every 200 flight hours, where the inspection and low observable restoration occupied close to 44 days. The long range goal is to increase time between overhaul to 400hr and then 600hr. The inspection interval for stealth degradation is every 18 months.

The F-22 is claimed to reduce by half the number of maintenance people needed per aircraft (to 8.7 from 16.6 for the F-15). However, the RCS modifications referred to above included the number of engine access doors being reduced from 3 to 2 per engine. This will surely increase the task of maintenance and make it harder to achieve the reduction to 12 MMH/FH for the F-22 from 15 MMH/FH for the F-15 and engine change time to 1.5hr from 2.5hr [14]. The equivalent numbers for the EF2000 are 9 MMH/FH and the time for four personnel to change two EJ200 engines is 0.75hr [16]

The two largest maintenance problems of the F-117A are reckoned to be the aircraft's exterior, especially the RAM and exhaust system. Removing panels to perform maintenance involves a laborious process of chipping and scraping RAM off with putty knives. Several attempts to incorporate electric hand tools, have proved less satisfactory than manual methods. In addition the RAM suffers due to rain and fuel leaks in the fall and spring due to fluctuating temperatures [17]. To mitigate RAM-related maintenance burdens, the fighters routinely fly training sorties with some RAM removed, and pilots try to avoid weather that could degrade the surface [18]. After experience with the aircraft's exhaust system in the Gulf War, modified heat shields, seals, airflow paths and thermal protection bricks at the edge of the nozzle tiling improved its maintainability. Designed 15 years ago the exhaust system became one of the most burdensome areas of the aircraft. Nevertheless the aircraft is claimed to require roughly the same MMH/FH as the F-15C [18].

RADAR ABSORBING MATERIALS

A good, low RCS aircraft design should exploit shaping to the greatest possible extent. However, there are situations where shaping may be inappropriate or fail to meet one's objective in full. In these cases the aircraft designer turns to RAM in either the design phase or as a retrofit. The use of RAM could reduce the F-15's RCS by a factor of 10 but, as noted above, because radar signal strength weakens as the fourth power of the distance this would result in a relatively small reduction of detection range. RAF fighters employed in the Gulf War were treated with RAM in an effort to reduce their RCS, by gluing RAM tiles inside inlets and painting radar absorbing paint (RAP) on the leading edges of fins, wings and tails.

As its name implies, RAM is intended to reduce the scattered signal by absorbing some part of the incident radiation. Microwave energy is converted into heat energy with hardly any noticeable temperature rise because the energies involved are extremely small. Various kinds of material can be made to absorb microwave energy by impregnating them with conducting materials such as carbon and iron. The challenge in designing absorbers is to obtain desired performance over the widest range of frequencies and aspect angles used.

In the main, there are two currently used kinds of absorbers, called dielectric RAM and magnetic RAM. Addition of carbon products in an insulating material introduces electric resistance and changes the electrical properties. Hence carbon-based absorbers are called dielectric RAM. The most familiar examples are pyramidal absorbers found in anechoic chambers. Dielectric RAM is usually too bulky and fragile and not attractive where space is limited and severe mechanical vibrations exist. Magnetic RAM uses iron products such as carbonyl iron and iron oxides called ferrites. Iron effectively dissipates radar waves and has been used in aircraft paint. It is quite effective against the high-frequency radars used in modern fighters. Unlike dielectric RAM, magnetic RAM is compact, thin and of adequate strength to withstand loads and an abrasive environment. Nevertheless, its thickness does rob volume from volume-limited aircraft. Furthermore, it is heavy, expensive and its performance deteriorates as operational temperatures approach the Curie point[4] (500-1000°F or 530-800K) but this does make it suitable for Mach 2+ aircraft. The materials are usually embedded in a form of rubber tile, as so-called parasitic RAM, which can then be glued in position and they are suitable for inlet ducts. For high temperature applications, such as around the nozzle of the engine then use has to be made of ceramic-based RAM.

The current emphasis in RAM development is placed on finding lighter, cheaper and wider band absorption stealth coatings that would allow reduced thickness of layers to be used[19]. Since the Gulf War, portions of the F-117A's surface have been improved with new coating to reduce radar reflections at all frequencies and to suppress 60-70% of infrared emissions in the critical 3-5 and 8-12 micron range. Such coatings are embedded with modified carbon molecules. When low voltages are passed through such coatings, their ability to absorb radar energy and contain heat is increased[20].

Little information has been released on radar absorbing paint (RAP) which is a ferrite paint (often referred to as iron ball paint). This is, apparently, a polyurethane-based sprayable coating that has the advantage of being able to be sprayed in varying thickness and can additionally provide an electrical bond between adjacent panels. Apparently, a thickness of 0.03in will reduce the reflected energy by an amount increasing from 3dB at 6 GHz to 13dB at 18GHz[21]. However, just how easy it is to accurately apply such thin layers during maintenance is questionable. Since all iron-based materials are liable to oxidation, then certainly for shipboard-based aircraft, effective measures have to be taken to minimise the extra maintenance required. An additional problem is the familiar one of galvanic corrosion due to the dissimilar materials. In the case of the F/A-18E/F, over 150lb of corrosion-proof RAM has been used on the aircraft's inlet and radar cavity[22]. Corrosion-proofing has reduced anticipated MMH/FH by over one to meet the target requirement of 12 (current F-18s have an in-service record of 16.5 MMH/FH)[23].

USE OF CARBON FIBRE COMPOSITES

Carbon fibre composites (CFC) have been employed for some time (Fig 9[24]) to give increased strength/weight and stiffness/weight in aircraft structures, the benefits of which can counter the weight increase due to signature control. One of the consequences of CFC usage is that lightning attachments do not have the current paths available on metallic structures. This gives rise to potential skin damage and sparking. Such effects are unacceptable in integral wing tanks. Lightning protection for the British Aerospace Experimental Aircraft Programme (EAP) was designed into the wing involving aluminium strips on the external surface, thin metallic mesh over the thin skin areas and other insulating and conducting measures. It was the first aircraft with CFC integral fuel tanks to be designed to withstand the 200kA lightning strike threat[25]. However, mixtures of conducting metals and non-conducting materials causes radar scattering at joints, e.g. canopy, radomes, doors.

Concern has been raised over the effect of airframe deflections on RCS. Use of CFCs make for stiffer structures and during the proof load tests on the B-2 with 172ft span, wingtip deflection was about 18in compared with 18ft for the B-52 wing (admittedly of much higher aspect ratio) at the same load condition[26]. The B-2 has a penetration mode control surface deflection limiter to minimise RCS when manoeuvring during an attack[11]

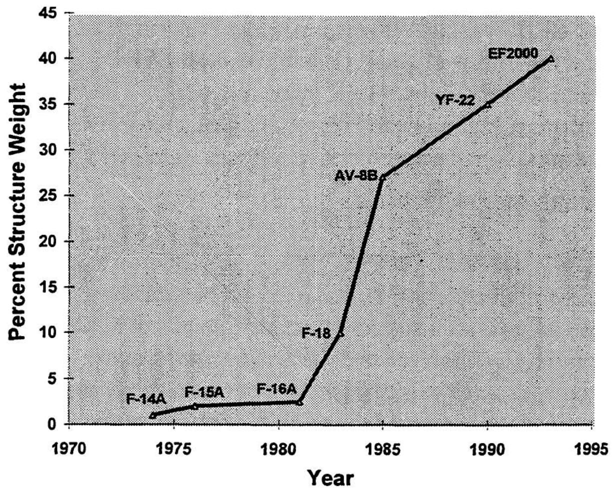

Figure 9 The growth in the use of carbon fibre composites[24]

DECOYS

The deployment of decoys can saturate an air defence system thereby minimising the loss of aircraft by forcing the wasteful expenditure of threat munitions. Decoys are used not for signature reduction, but rather, signature *control* for deception purposes. Decoy vehicles have to mimic the signature characteristics of the actual aircraft, including not only the absolute levels they have (so the decoys have artificially-enhanced signatures) but also signature fluctuation rates. As threat sensor capabilities improve there will be a requirement to mimic even the signature information that can be extracted via signal processing techniques, such as imaging IR.

While an aircraft can eject both flares and chaff simultaneously, later separation of the two types of decoys (IR and radar) occurs because of their quite different aerodynamic behaviour. Pulse-Doppler radars can easily distinguish a target from a free-floating decoy. A towed decoy overcomes this problem and can provide a single source using a flare and corner reflector. The Defensive Aids Sub-System (DASS) on EF2000 is a critical subsystem which should add considerably to combat effectiveness and is reputed to cost $4.5M per aircraft [16] and given the relatively unstealthy nature of the aircraft DASS will be fully utilised during combat. EF2000's towed decoy will be able to deploy and tow throughout the flight envelope [27]

THE FUTURE

On the basis of much independent research carried out during the 1980s the USAF stated in 1989 that no defensive concept would negate the value of stealth technology in the foreseeable future [28]. Over 40 potential means of defeating stealth were investigated in the programme [29]. It is interesting to note that by 1995, it was recognised that systems and techniques (especially low frequency systems) do exist which can detect even the B-2. Because the required thickness of RAM is so large and aircraft shaping has little effect at the lower radar frequencies, current stealth capacity is limited to the shorter wavelengths (frequency range of 3-10GHz. Long wavelengths are less affected by the small details of shape and absorbent structures. Though current stealth technology may frustrate modern air defence radars the same would not be true of older long wavelength (lower frequency) radars that have been kept operational worldwide. Some countries were prompted to do this not because of low RCS aircraft but from the desire to overlap many different types of radar to make them more difficult to jam.

However, all airborne target data detected by long range surveillance radars must eventually be passed to aircraft or SAM sites. These are equipped with high frequency tracking and targeting radars that can be defeated by RAM and shaping. How effectively surveillance radar systems could hand-over to shorter wavelength sensors is questionable.

Currently the USAF is investing in two classified stealthy aircraft (excluding Darkstar) but there are differences among stealth advocates over what kind and what degree of invisibility will be enough in the 21st Century [8]. There are advocates on both sides of the argument. There are those who, when referring to low-observables (LO) mean *very* LO, that is, a very large reduction in RCS. They argue that aircraft have to be designed for VLO and it cannot be achieved by adding new materials and coatings to existing aircraft. Investment in stealth is, however, heavily influenced by declining defence budgets. At present US Air Force VLO efforts represent only a fraction (15%) of what it was previously. Even on the F-22 the need to cut costs has inevitably led to suggestions of cutting stealth.

Other defence officials do not believe that an aircraft has to have VLO to be effective. The US Navy, for example, has staked its immediate aviation future on an $81-billion investment in the F/A-18E/F. This is not a VLO design but one that uses the addition of new materials, some reshaping and coatings. Stealth advocates note that much of the effect will be lost because bombs, tanks and missiles hung from wing pylons will increase the RCS greatly.

Thus, with even stealthy aircraft being vulnerable at least to detection by some kinds of low frequency radars, it must come as no surprise that precision, cruise type weapons appear to have a large representation among current classified programmes. It may be that, though a few years ago, it was thought that a large fleet of VLO aircraft would be needed, a more modest investment would be more sensible [30]. It may be, as the advocates of the EF2000 feel, that the use of VLO aircraft and missiles is not the most reasonable nor affordable answer (Table 2). Vehicles with some frontal stealth, including reduced signature versions of today's aircraft backed up with a modest stealth fleet and stand-off jamming and deception could do the job. Full VLO is only required some of the time and there are many more targets that do not justify VLO. Less stealthy assets may be able to do the job and much more cheaply.

The seeker heads of AIM-9 type weapons have a disproportionately large frontal RCS [31] and instead of concentrating on airframes, the focus may be on the external carriage of stealthy weapons (conventional shapes with RAM treatment and/or conformally-mounted). A good stand-off weapon with a long range coupled with high terminal accuracy diminishes the need for VLO.

CONCLUSION

While signature control is necessary to achieve acceptable exchange ratios and improve survivability, a major lesson of aircraft design is that you don't get something for nothing. The key will be how to keep new aircraft affordable and this will only happen if there is no 'requirements creep' [32]. There are penalties to be paid and trade-offs to be made.

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	British Aerospace		Defence Research Agency	
Fighter	**Effectiveness**	**Inferred exchange ratio***	**≈Effectiveness**	**Inferred exchange ratio***
F-22	0.91	10:1	0.9	9:1
EF2000	0.82	4.5:1	0.75	3:1
F-15F	0.6	1.5:1		
F-15E			0.55	1.2:1
Rafale	0.5	1.1	0.5	1:1
F-15C	0.43	1:1.3		
F-18E/F	0.25	1:3	0.45	1:1.2
F-18C	0.21	1:3.8		
F-16C	0.21	1:3.8		
Gripen			0.4	1:1.5
Mirage 2000			0.35	1:1.8
Tornado F.3			0.3	1:2.3

* Assumed exchange ratio (enemy to friendly killed) inferred from effectiveness scores.

≈ Approximate values

Table 2 Fighter comparisons from combat simulations [7]

Combat simulations carried out in the UK by British Aerospace for small engagements (2 v 2) and the independent Defence Research Agency (DRA) for up to 8 v 8 produced the scores shown in Table 1. It can be seen that the EF2000 is superior to all fighters except the F-22, which is three times better in terms of exchange ratio. Though the data should be treated with skepticism, it does point out the advantages of low RCS and stealthiness in general.