STEALTH TECHNOLOGY

Stealth or “low observable” (LO) technology involves making vehicles or craft less visible or even invisible. It can be used by military, police, coast guards (and the people trying to evade them!), hunters, photographers etc. It encompasses a range of methods designed to reduce the detectability of ships, submarines, aircraft, land vehicles, missiles, space vehicles, buildings, people and any other item that is to be concealed.

by Dr David Maddison

Vehicles, people and munitions can be detected by a variety of means. This includes visually, from infrared emissions, electromagnetic emissions, sound, wakes, reflections of radar, lidar or sound waves (SONAR), or by any other process or energy emission that will reveal their presence.

All these factors combine to produce a detectable “signature”. Stealth technology is all about reducing that signature.

Stealth can be achieved through active and passive electronics, material composition, surface treatments, object shaping, colouring, lighting, heating, cooling and acoustics. Tactics are also important (eg, which altitude an aircraft flies at, or which path a human takes through terrain).

All elements of the signature must be addressed for proper stealth.

As with most technology, implementing stealth is not a once-only strategy. Detection technology is also improving all the time.

Weaknesses are always being found in concealment and measures for finding the concealed platform, so ongoing development is required for both sides.

Indeed, countries which have developed the best stealth technology likely also have excellent detection technology. Otherwise, they could be surprised by attacks using stealth technology that they didn’t know their enemies had.

History of stealth

Apart from camouflage clothing, which has been around since pre-history, one of the first attempts at stealth in the modern era was in WWI. Germany experimented by using transparent fabric on its aircraft, to make them less visible to the human eye. Interior parts were painted in light colours to help hide them (Fig.1).

Similarly, in 1935, the Soviets modified a Yakovlev AIR-4 to make the Kozlov PS (or Prozrachnyy Samolyot), a transparent aircraft.

During WWII, Germany experimented with stealthy anti-radar and anti-sonar coatings on its submarines.

The German Horten Ho 229 from WWII was a ‘flying wing’ type aircraft developed late in the war. Flying wings are intrinsically more stealthy than conventional designs, but its shape was dictated more by fuel efficiency than stealth (early jet engines were very inefficient).

In 2008, Northrop Grumman reproduced the aircraft and tested its radar cross-section, determining that it had a detection range 20% less than a conventional WWII fighter. Combined with its very high top speed, it could have changed the outcome of the war had it been produced in sufficient numbers.

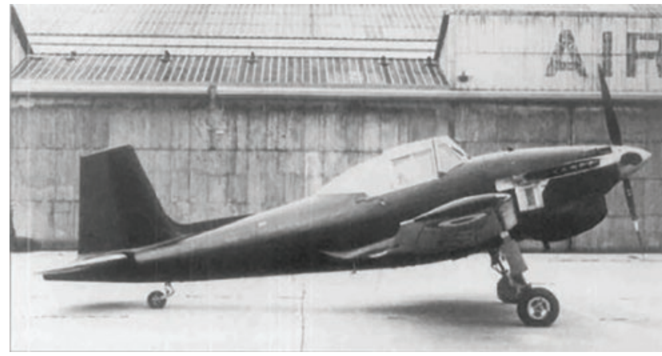


Fig.1 (left): artist's concept (bottom) of German "invisible" plane from WWI. *Image source: siliconchip.com.au/link/aaz5*

Fig.2 (above): the 1950 Boulton Paul Balliol with DX3 radar absorbing material.

See the video titled *"Stealth Fighter Greatest Mysteries of WWII Hitler's Secret Weapons Recreated"* at **siliconchip.com.au/link/aaz9**

Also during WWII, the Germans used anti-sonar tiles on submarines. The Soviets adopted them in the 1970s, and the US and UK from the 1980s.

In 1945, the US Massachusetts Institute of Technology (MIT) developed radar absorbing-paint for aircraft. The paint was known as MX-410 and contained disc-like aluminium particles in a rubber matrix, but it was too heavy to be practical.

The British Boulton Paul "Balliol" first flew in 1950. It could be regarded as the first aircraft with radar stealth properties (Fig.2). Two were used to test radar-absorbent rubber-like "DX3" coating materials in the 1950s. It was designed to defeat radar in the X band, 8-12GHz.

Following the Balliol, the British also tested DX3 on a Canberra bomber in 1957, designated WK161. Testing continued until 1963. It also had a special engine nacelle design to reduce radar reflections from the jet turbine.

After the shooting down of the American U-2 spy plane over the Soviet Union in 1960 and the capture of its pilot, Gary Powers, it became urgent for the USA to develop anti-radar stealth technology. This lead to the stealthy Lockheed A-12 and its descendant the SR-71 Blackbird (Figs.3-5), and subsequent aircraft discussed below.

The SR-71 Blackbird flew from 1964 to 1998. It had features which gave it a low radar cross-section at the high altitudes it flew, including paint that contained ferrite balls, rudders canted at 10° and alternating wedges of titanium and honeycomb plastic composite material on leading and trailing edges, to break up radar signals.

The 'father' of modern low-observable platforms

An important area of stealth technology is the interaction between radar beams and vehicle surfaces.

It was a Russian, Pyotr Yakovlevich Ufimtsev, who established the theoretical basis for the reflection of electromagnetic radiation from various objects. The Soviets permitted him to publish his work as they saw no military or economic value in it.

The English title of the book he published in Russian in

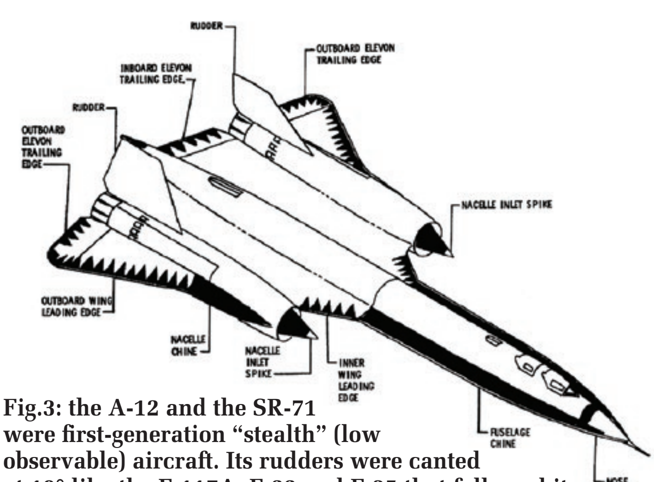


Fig.3: the A-12 and the SR-71 were first-generation "stealth" (low observable) aircraft. Its rudders were canted at 10° like the F-117A, F-22 and F-35 that followed it. While it was low observable for the time, it made no major aerodynamic concessions to this aspect; it was built for speed.

Fig.4: an SR-71 Blackbird under construction, showing the wedges in the wing trailing edges (from siliconchip.com.au/link/aaza).

Fig.5: the US SR-71 in flight. The history of stealth and the Blackbird is covered in the book "From Rainbow to Gusto: Stealth and the Design of the Lockheed Blackbird" by Paul A. Suhler.

1962 was "Method of Edge Waves in the Physical Theory of Diffraction", and it was translated by the US Air Force and published in 1971. You can download a free copy via **http://siliconchip.com.au/link/aazb**

The book caught the attention of American engineer Denys Overholser at Lockheed. He realised that it provided the theoretical foundation to build a stealth aircraft, which lead to the development of the first operational stealth aircraft, the F-117A (Figs.6 & 7). Its development started in 1975, and a demonstrator first flew in 1977. It was not known to the public until 1988.

Engineers at Northrop also used the theory to program supercomputers to optimise the design of the B-2 bomber (Figs.8), a much more sophisticated design than the F-117A. This was because the computer power to implement the B-2 design was not available when the F-117A was designed.

Fig.7: the US F-117A flew from 1981 to 2008. It was the first purpose-built production stealth aircraft, designed to have a low radar and infrared signature.

Fig.6: the Lockheed "Have Blue" HB1001 proof-of-concept stealth technology demonstrator. It was developed into the F-117A Nighthawk which first flew in 1977 and was the first aircraft whose shape was specifically designed to minimise radar cross-section. Two prototypes were built; both crashed, but the stealth concept was proven.

The B-2 is highly aerodynamically efficient, as is typical of flying wing designs, and thus has a long range. Like the F-117A, it requires computer assistance to maintain stable flight. The B-2 has its origins in the Northrop YB-49 flying wing prototype of 1947, only one of which was produced.

The F-117A was withdrawn from service in the US Air Force in 2008, as it was replaced by the far superior F-22 (Fig.9).

Ben Rich, the head of Lockheed's "Skunk Works" which developed the F-117A, referred to Professor Ufimtsev's work

Fig.8(a): the US Northrop Grumman B-2 Spirit bomber, in service since 1997. Jack Northrop worked on the YB-49 and so was given special permission in his retirement to see the design of the B-2; he was overwhelmed with happiness.

Fig.8(b): the YB-49, in a sense the predecessor of the B-2.

Fig.9: the US F-22. It is a highly capable aircraft – possibly the stealthiest ever built – but the program was cancelled due to cost after just 195 of a planned 750 were built.

as "the Rosetta Stone breakthrough for stealth technology". He is also regarded as the "father of stealth".

He described how, when the F-117A was being developed, a precursor model was mounted on a pole for radar range testing. A test operator said that it wasn't on the pole yet as there was no detectable radar return. Then a bird landed on the model, and it could be detected. That gives an idea of the low radar signature of that aircraft.

The F-117A used simple faceted flat panels which reflect radar away from threat directions, but that left it somewhat visible in other directions. On the more advanced B-2, all surfaces are curved, so radar reflections are minimal in all directions. The B-2 also has superior aerodynamics due to the use of curved rather than flat surfaces.

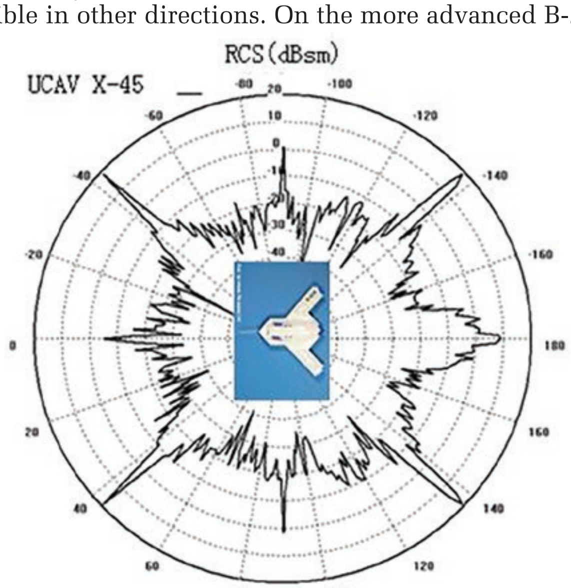


Fig.10: a calculated radar cross-section plot based on the published shape of a US X-45 drone, as presented by Chinese researchers at: siliconchip.com.au/link/aaz6 The actual RCS is classified, but this approximation demonstrates the effect of shaping on the radar return from various angles. Stealth design aims to reduce the spikes.

Radar cross-section

The radar cross-section (RCS) of an object can be minimised to reduce its visibility to radar. This is a measure of an object's reflectivity to the radar frequencies of interest.

The radar cross-section of an object is dependent up the following: the radar angle of incidence (object orientation), the size of the object, the geometry of the object and the radar frequency (different materials absorb or reflect radar differently at different frequencies).

The RCS is defined as the size of the projected area of a

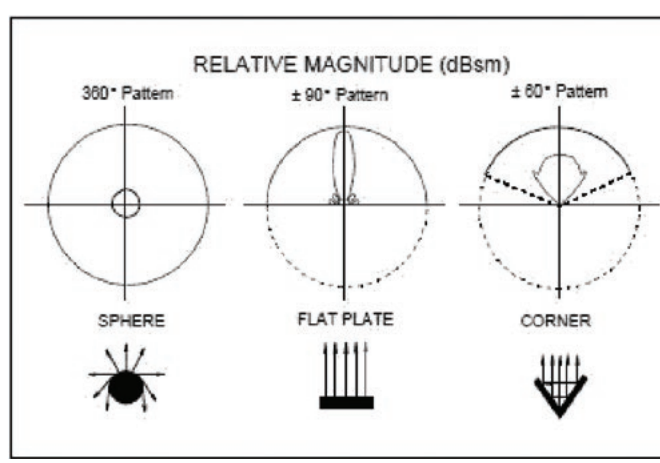


Fig.11: the radar cross-section of some basic shapes. Flat surfaces at right angles to the incoming radar signal are avoided in stealth designs and corners even more so. "Corner reflectors" are used when one wants to specifically make something visible to radar, such as a weather balloon.

Aircraft	Country	Type	Year	RCS (m^2)
B-52	USA	Bomber	1955	100-125
F-15 Eagle	USA	Fighter/bomber	1976	10-25
Su-27	USSR/Russia	Fighter/bomber	1984	10-15
F-4 Phantom	USA	Fighter	1960	6-10
F-16A Fighting Falcon	USA	Fighter	1978	5
Su-30MKI	Russia	Fighter/bomber	2002	4
MiG-21	USSR	Fighter	1959	3
F-16C Fighting Falcon	USA	Fighter	1978	1.2
Human	Various	Procrastinator	?	1
F-18C/D Hornet	USA	Fighter	1984	1-3
B-1B Lancer	USA	Bomber	1986	0.75-1
Rafale	France	Fighter	2001	0.1-class
F/A-18E/F Super Hornet	USA	Fighter/bomber	1999	0.1-class
Eurofighter Typhoon	UK/DE/IT/ES	Fighter	2003	0.1-class
F-16IN Super Viper	USA	Fighter	2011	0.1-class
B-2 Spirit	USA	Stealth bomber	1997	0.1 or less
F-117A Nighthawk	USA	Stealth bomber	1983	0.025 or less
Bird	Sky	Worm eater	?	0.01
SR-71 Blackbird and A-12	USA	Reconnaissance	1966	0.01
F-35 Lightning II	USA	Fighter/bomber	2006	0.0015-0.005
F-22 Raptor	USA	Fighter	2005	0.0001-0.0005
Insect	Swamp	Pest	?	0.00001

Table1: radar cross section (RCS) of various aircraft and creatures

sphere which would give an equivalent radar return to the object illuminated by the radar.

Table1 gives such figures for many modern military aircraft, taken from a public source (www.globalsecurity.org).

The RCS can be represented as a polar plot in which the strength of a radar reflection is plotted as a function of the incident angle of the radar beam (Fig.10).

Reducing radar cross-section

There are three main methods to reduce the RCS:

1) Reducing the number of surfaces capable of reflecting a radar beam back to the receiver, eg, having no surfaces at right angles to the incoming radar (see Figs.11-13).

For example, the turbine blades of jet engines which must be hidden from direct impingement by the radar beam as they are effectively flat surfaces facing in the direction of flight (Fig.14).

2) Where shaping by design is not possible, or susceptible surfaces responsible for a high radar return cannot be eliminated, they can be coated with radar absorbing materials (RAM).

3) Using electronic countermeasures to jam or fool enemy radar, such as by presenting an attractive decoy target to a radar-guided missile (see Fig.22).

There are also dedicated electronic countermeasures aircraft for this purpose such as Australia's EA-18G Growler electronic attack aircraft (see our article on the Avalon Airshow from May 2019, p15; siliconchip.com.au/Article/11612).

Tactics are also important, such as making sure that vulnerable angles of the aircraft with higher radar returns are not presented to the enemy. Poor tactics were responsible for the destruction of an F-117A, as described in the panel later.

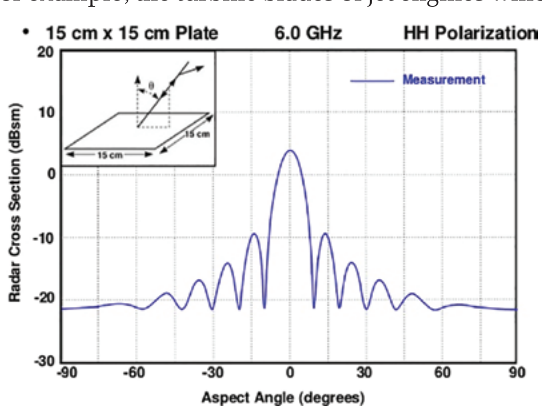


Fig.12: the RCS of a square plate 15x15cm as a function of the incident radar wave angle. The maximum reflection of ~4dB occurs at 0°, meaning that the 0.0225m^2 plate looks bigger at 0.0565m^2, while at an angle of 30°, the reflection is around -21dB, so the plate looks smaller, equivalent to 0.00018m^2. Image courtesy IEEE.

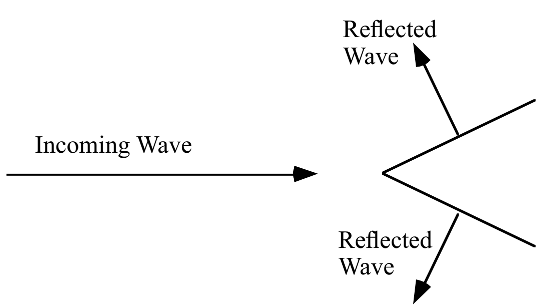
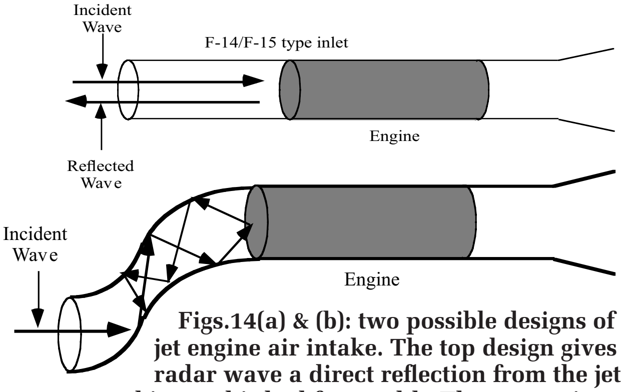


Fig.13: a basic shaping to reduce radar returns. It's designed so that the reflections are away from the incoming wave. Image source: W.H. Mason, "Fifteen Minutes of Stealth in Aircraft Design".



Figs.14(a) & (b): two possible designs of jet engine air intake. The top design gives a radar wave a direct reflection from the jet turbine and is bad for stealth. The serpentine design at the bottom is better, as the air inlet can be coated with radar absorbing materials to reduce the radar reflection. But the circuitous path is not the best for engine efficiency, and is difficult to model in the design stage. *Image source: W.H. Mason.*

Fig.15: a Lockheed Martin F-35 Lightning II stealth fighter in Australian livery.

Radar absorbing materials (RAM) and paint (RAP)

Reflected radar signal strength is directly proportional to the radar cross-section and inversely proportional to the fourth power of the distance, so if large amounts of radar energy can be absorbed, the detection range can be reduced.

It was suggested in "The Fundamentals of Fighter Design" by Ray Whitford (2000) that it would be of tactical significance to reduce the distance at which an enemy radar can detect a stealth aircraft to 18% of that for a non-stealth aircraft.

This requires a relative radar return strength of $0.18^4 = 0.001$, meaning that a stealth aircraft must have an RCS 1000 times lower than a regular aircraft. So stealth treatments have to be highly effective to be tactically meaningful.

The purpose of RAM and RAP is to absorb radar or other radio energy of a specified frequency and dissipate it as heat. Ideally, these materials should be as broadband in their frequency response as possible, but there are practical limitations to this.

Other requirements include durability, low weight, minimal thickness, low cost (especially for large platforms such as ships) and ideally, the ability to easily adjust the material composition to suit different frequency requirements.

There are several types of radar absorbing materials. Note that plastic composites with non-conductive reinforcement such as Kevlar or fibreglass do not reflect radar signals anywhere near as much as metals. It is even possible to produce structural RAM, where the platform structure itself absorbs radar.

Dielectric RAM consists of electrically lossy filler particles, such as carbon black, in a foam, resin or rubber matrix. Certain fillers of the right dimensions can, in addition to electrical losses, produce a destructive interference effect. The RAM structure may consist of two or more layers with different properties, to achieve the desired broadband absorption.

Magnetic RAM is often in the form of paint which has magnetic spheres of ferrite or carbonyl iron embedded in an insulating matrix such as rubber or epoxy. Electromagnetic energy is lost in the ferrite or iron particles and energy is absorbed. This type of material is characterised by good bandwidth and absorption at reasonably low thickness. A disadvantage is that these materials are relatively heavy.

Such paints were used on the SR-71 and the F-117A.

In both magnetic and dielectric RAM, a continuous gradation of properties through the thickness of the material might also be used, such as a layer that has a small concentration of carbon or ferrite at the front and a much higher concentration at the rear.

Hybrid RAM may have a combination of magnetic and dielectric RAM to achieve a more broadband response and lesser thickness.

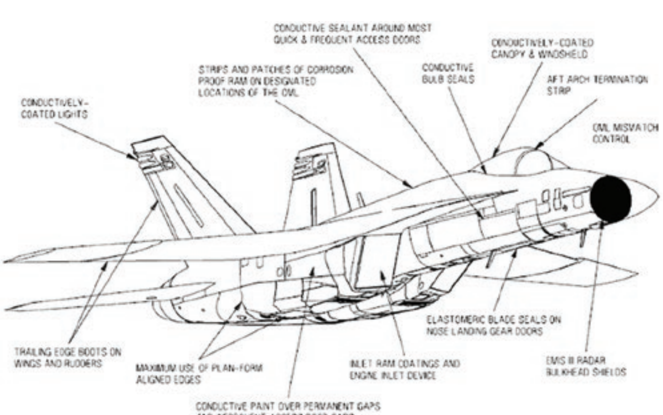


Fig.16: various treatments to reduce the radar cross-section of the F/A-18E/F Super Hornet. *Source: siliconchip.com.au/link/aaz7*

Fig.17: the Russian SU-57 fifth-generation stealth fighter.

Fig.18: the Chinese Chengdu J-20 fifth-generation stealth fighter.

Fig.19: the first known stealth helicopter, the Hughes 500P "Quiet One" in Laos during the Vietnam war.

A split-ring resonator can also be used. This is a type of metamaterial (see Fig.26).

A Salisbury Screen is a type of narrow-band dielectric absorber which consists of a resistive coating, a spacer of one quarter the wavelength to be absorbed and a metal backing plate. It is simple in concept but not generally used in stealth applications. A Jaumann absorber, first used in 1943, is a variation of this; it is like a multi-layer Salisbury Screen and can absorb two wavelengths.

Efforts are underway to develop RAMs with properties which can be changed dynamically to suit the required conditions. Note that RAMs can be used on certain civilian structures to reduce undesired reflections, such as the interference to radar systems caused by wind turbines.

Electronic emissions

These should be eliminated where possible. An aircraft whose own radar emissions can be picked up by passive sensors at long distances is not very stealthy; stealth aircraft generally have 'low probability of intercept' (LPI) radars. They are usually electronically-scanned phased-array types, as they can scan much faster than traditional radars.

Emissions shielding is also required around cockpit equipment, and gaps around access doors need to be electrically continuous to reduce the electronic noise leakage.

Fig.20: a comparison of a standard Black Hawk helicopter (as used by Australia) and the stealth version, which has an extra rear rotor blade, and the main rotor has down-turned tips. The stealth version is also much smoother, with fewer protuberances, plus angled sides which are likely made of or coated with radar absorbing materials.

Other stealth aircraft

The US Lockheed U-2 spy plane (operational in 1957) was thought to be untrackable with Soviet radar due to the altitude at which it flew (70,000ft). It is now known that the Soviets tracked every single flight, but they did not have an antiaircraft missile capability to shoot it down. That infamously changed in 1960 when one was shot down by an SA-2 missile

Attempts were made to reduce the plane's RCS under the auspices of the CIA's "Project RAINBOW". Techniques included "wallpaper" sheets with an electrically conductive printed circuit pattern (a type of metamaterial, see below) attached to the fuselage to absorb radar signals.

There was also a system of wires called the "trapeze" to reduce reflections from lower frequency 65-85MHz long-range radars. These were attached about 30cm from the wing leading and trailing edges, and other wires with precisely-placed ferrite beads designed to reduce the reflection from the fuselage and vertical stabiliser.

These measures were unpopular with pilots and also caused a fatal crash, which led to their abandonment in 1958.

The US aircraft which followed, explicitly designed to have low radar signatures, are the F-117A, B-2, F-22 and F-35 (Fig.15). Other aircraft, such as the F/A-18E/F, have been modified to reduce their signature (Fig.16), but are not purpose-built "stealth aircraft". The A-12 and SR-71 mentioned above had certain stealth design elements but were not fully designed for stealth.

The Russian SU-57 (Fig.17) is a stealthy fifth-generation fighter like the F-35, as is the Chinese J-20 (Fig.18).

Australia also has a stealthy UCAV (unmanned combat aerial vehicle) under development. It is the Boeing "Loyal Wingman" which was described on page 13 of our May 2019 issue (**siliconchip.com.au/Article/11612**). It is expected to fly sometime this year. See the video *"Boeing Airpower Teaming System: A smart unmanned team for global forces"* at **siliconchip.com.au/link/aazc**

Stealth helicopters

Helicopters are intrinsically difficult to make stealthy because of the shape of the rotor blades, tail rotor and control

Fig.21: a Revell plastic model of the Russian Kamov Ka-58 stealth helicopter. The model was based on information accidentally released by the Russians in October 2018.

Fig.22: the Australian-developed Nulka decoy; Australia's largest defence export, worth $1 billion in export revenue. It is more effective if the radar signature of the ship it is protecting is minimised, so the Nulka presents a larger target.

gear. These present a large and constantly changing variety of angles for radar to reflect from, plus a substantial acoustic signature.

Nevertheless, helicopters are a valuable military asset and it is worth making an effort to reduce their signature. The existence of stealth helicopters mostly came into public knowledge with their use in the raid on Osama bin Laden.

The first known stealth helicopter was a modified Hughes 500 or OH-6A called the 500P (Fig.19) where "P" was for penetrator. The CIA used this during the Vietnam War. It was designed for acoustic stealth rather than radar or visual/infrared stealth, and it was known as "The Quiet One".

Research started as early as 1968, and it was built to perform one specific covert operation in December 1972, which was to tap into a phone line deep inside enemy territory to see if the North Vietnamese were adhering to peace terms.

The tail rotor was determined to be one of the chief sources of noise. By doubling the number of blades, the speed of the rotor was halved, reducing noise dramatically. Additional modifications included an extra main rotor blade for a total of five, alterations to the blade tips, an engine exhaust muffler and lead pads to reduce vibrations from the aircraft skin.

The distinctive "chop, chop, chop" noise of helicopters arises from the main rotor blade creating vortices at the blade tips, which are subsequently struck by the following blade. The blade tip modifications minimised this, and the extra blade allowed the main rotor speed to be reduced. The helicopters weren't silent, but they produced less of the type of noises that most people would notice.

Tests were conducted at the famous Area 51 in Nevada. Don Stephens, who managed the Quiet One's secret base in Laos for the CIA said "It was absolutely amazing just how quiet those copters were. I'd stand on the [landing pad] and try to figure out the first time I could hear it and which direction it was coming from. I couldn't place it until it was one or two hundred yards away."

Rod Taylor, who served as the project engineer for Hughes, said: "There is no helicopter today that is as quiet." At least one of these helicopters is still in service today with a private company. See the video *"Former NOH-6P Quiet One – Startup"* at **http://siliconchip.com.au/link/aazd**

The Sikorsky UH-60 Black Hawk is a US military helicopter (also used by Australia) and a (then) secret stealth version was used in the 2011 raid on Osama bin Laden in Pakistan. It was reported that it had extra blades on the tail rotor as a noise reduction measure, and various surface features and materials consistent with stealth technology (Fig.20).

The Russians also have a stealth helicopter, the Kamov Ka-58 (Fig.21). The Russians accidentally disclosed its existence in October 2018.

Stealth ships

It is vital to manage the radar, infrared and other signatures of ships. One objective in reducing the RCS of a ship

Fig.23: the USS Zumwalt stealth ship. It needs to use reflectors to make it visible to maritime radar to avoid collisions. The program was cancelled due to the huge expense.

Fig.24: the stealthy Lockheed Martin LRASM Long Range Anti-Ship Missile.

Fig.25: F-35 stealth fighters launching low observable JSMs.

is making a decoy such as the Australian developed Nulka (Fig.22) a more attractive target for missiles.

The Nulka is a hovering rocket which is launched from a ship when a hostile missile is detected, to lure anti-ship missiles away from their intended target. It is in use by Australia, Canada and the USA. It was successfully used in combat, when US ships off the Yemeni coast came under enemy missile fire.

The USA produced a stealth ship in the form of the Zumwalt class (Fig.23), but the program was cancelled due to high costs. See the video *"Zumwalt - destroyer from the future"* at **siliconchip.com.au/link/aaze**

Other navies have stealth ships, mostly experimental, with a few in service. It is possible to retrofit existing ships to reduce their signature, such as with the fitment of RAMs or the retrofitting of a simpler mast design with fewer reflecting surfaces.

Australia's CSIRO is developing smaller, stealthier antennas for Navy ships. To quote them, "We're looking to replace these with a small number of radio frequency antennas that are much more sensitive, lightweight, low-noise and as small as a Coca Cola can. The new technology aims to give the Navy greater stealth, safety, new functionality and cost savings."

Stealth missiles

The main defence a ship has against a missile which gets close enough to 'lock on' to it is to shoot the incoming missing down using a close-in weapons system (CIWS). A stealthy anti-ship missile is harder to defeat with a CIWS.

The USA has developed a stealth anti-ship missile which has artificial intelligence, called the AGM-158C Long Range Anti-Ship Missile (LRASM) – see Fig.24 and the video at **siliconchip.com.au/link/aazf**

The Joint Strike Missile (JSM), designed for use with the F-35 and other platforms, is also stealthy (Fig.25). It can be used against land and sea targets. Australia will use this missile and is funding the development of a new passive RF seeker for it, allowing it to locate targets based upon their "electronic signature" (the precise meaning of which is not specified) rather than radar or infrared signatures.

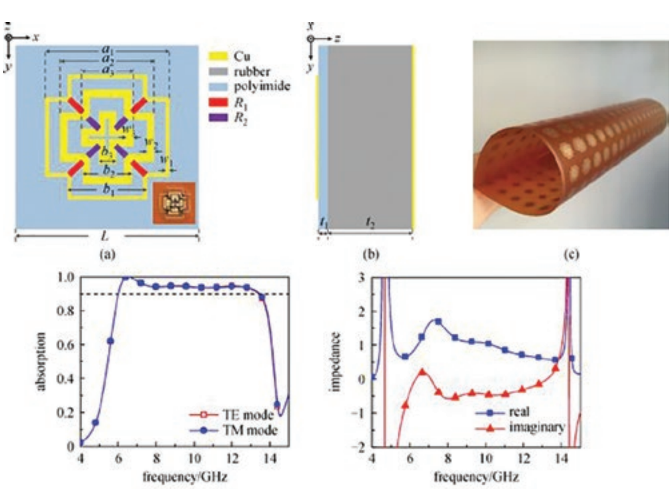


Fig.26: this split-ring resonator can be considered a resonant structure with some resistive elements. The structure is rubber with a polyimide coating on one side and copper on both sides. a1 = 9mm, t1 = 0.18mm, t2 = 3.5mm, R1 = 270Ω and R2 = 150Ω. TE is transverse electric and TM is transverse magnetic. *Image source:* *siliconchip.com.au/link/aaz8*

Fig.27: a Chinese GJ-11 Unmanned Combat Aerial Vehicle showing various stealth characteristics, including a shrouded exhaust to minimise infrared signature, blended wings, smooth shape, low overall profile and a flying wing design with no fuselage or tail fins. The result is a low radar signature. It has been suggested that this is not a real flying aircraft but a mockup.

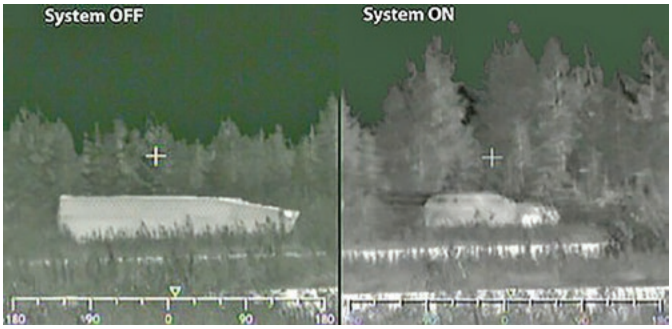


Fig.28: Adaptiv infrared stealth technology on an armoured vehicle with the system off and on. Panels are heated or cooled to give the appearance of a car when viewed with infrared imaging equipment.

This work is being carried out by BAE Systems Australia and Kongsberg Defence.

Metamaterials

Metamaterials are materials whose properties derive from their structure rather than the properties of the individual materials from which they are made. Structural elements typically include repeating patterns of specific shapes, sizes and orientation (Fig.26). Properties can be achieved that differ from the bulk properties of the material from which they are made.

For materials designed for electromagnetic applications, typically the structural elements have feature sizes smaller than the wavelength they are intended to interact with. For radar absorbing material applications, properties can be achieved such as broadband absorption or the ability to redirect the reflection of incoming radiation away from the source without specific surface shaping.

Metamaterials can also have favourable properties for applications such as acoustic absorbers in submarine hulls (see below).

Infrared stealth

Apart from reducing the RCS, it is also crucial to reduce a platform's infrared signature. For an aircraft, ship or armoured vehicle, the exhaust is the main source of infrared emissions. On an aircraft, this can be reduced by extensions around the nozzles to hide them from view at the angles that are to be most protected (Fig.27).

Cold air can also be mixed with the hot exhaust gases to lower the signature.

It is also desirable to reduce the infrared signature of the platform itself. This can be done by ensuring that there are no hot surfaces and also by using highly reflective paint to ensure a minimum of heating by the sun. Unfortunately, many materials that reflect infrared (desired) also reflect radar (not desired).

As with radar jamming, there are devices that emit infrared pulses to fool infrared seekers of missiles. Another common infrared heat-seeking missile countermeasure is to release flares, which may cause the missile to lock onto the wrong target.

Adaptiv is an infrared active camouflage system by BAE

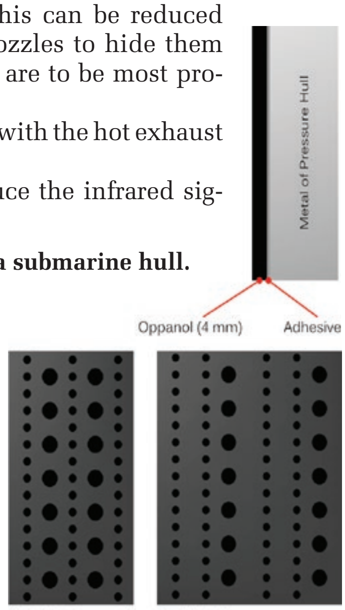
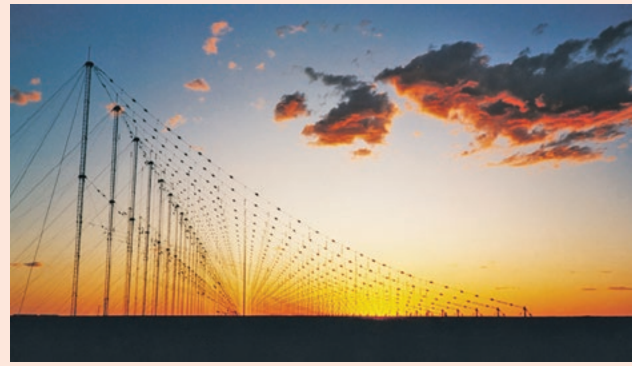


Fig.29: acoustic coatings for a submarine hull. They are typically made of a rubber-like material with holes containing air or solid inclusions of different properties on the hull side, while being smooth on the outside. The holes or inclusions scatter and absorb acoustic energy. These are "Alberich" tiles as used by Germany during WWII. *Image credit: Wikipedia user NZSnowman.*

The Jindalee Operational Radar Network (JORN)



JORN is an Australian over-the-horizon radar system used to defend Australia. It can detect aircraft and surface vessels at least 2000km from the mainland.

It allegedly can detect stealthy aircraft because it operates in the HF frequency band of 5-30MHz, while stealth aircraft are typically designed to avoid detection in the microwave spectrum (see siliconchip.com.au/link/aaz4).

Also, because it is an over-the-horizon system and the radar beam bounces of the ionosphere, the beam will strike aircraft from the top, which will have a higher radar reflectivity due to its flatness. Stealth aircraft designs are typically optimised for cases where the radar beam comes from a low angle (from a surface radar) or on the same plane (from other aircraft at a similar altitude).

Fig.30: acoustic tiles on a modern submarine; some that have fallen off due to defective adhesion. There is also what appears to be a vent. Adhesion of tiles to the hull is a problem; the tiles are relatively thick, heavy and expensive. Research aims to minimise these characteristics.

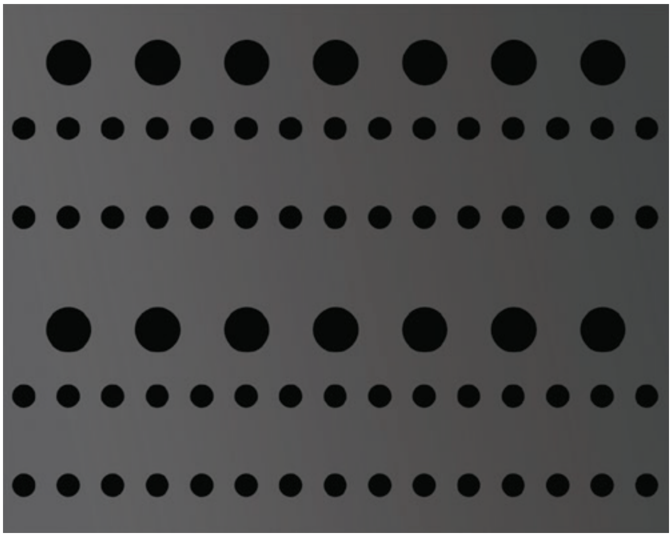


Fig.31: a clearer view of the repeating void/inclusion pattern within the German acoustic tiles.

Systems which variously heats or cools special panels on a vehicle to make it blend in with the background or appear something that it is not, such as a car (see Fig.28).

Visual signature

Visual signatures can be minimised by paint or camouflage schemes that blend in with the background, or to make the vehicle appear to be something that it's not or to appear in a different orientation, such as painting a fake canopy on the underside of an aircraft.

Aircraft and rocket engines also produce contrails or smoke under certain conditions, which can give away their position. Contrails can be minimised to some extent by special fuel additives or by flying the aircraft at an altitude where atmospheric conditions won't produce them. Smoke can be reduced by using smokeless rocket fuel.

Stealth submarines

There are two main aspects of stealth concerning submarines: acoustic and radar.

Acoustic stealth is designed to both minimise echoes reflected back to hostile active (search) sonar, plus reduce internally-generated sounds so they can't be heard by passive

Fig.33: the Fibrotex mobile multispectral camouflage system

Fig.32: a demonstration of the HyperStealth Quantum Stealth technology. Despite the name, there is no quantum mechanical effect involved.

(listening) sonar. The frequency response of the stealth system, usually hull-mounted tiles (Fig.29 – 31), should ideally be effective at all expected frequencies of sonar and internally generated noise.

Radar stealth is intended to minimise radar reflections from a submarine when it is surfaced, raises its periscope or uses its snorkel to ingest air for breathing or for diesel

The F-117A shootdown

In 1999, a US F-117A stealth aircraft was shot down by enemy forces in Yugoslavia. This came as a shock to the world, but it wasn't due to a deficiency in the aircraft stealth system, but rather poor tactics.

No platform is ever completely invisible to radar or other electromagnetic radiation, so the best tactic is to present to the enemy the angles of a platform that are least visible to radar (or infrared imaging system, etc).

In this case, the aircraft flew the same path on its bombing runs every night. Also, electronic countermeasures aircraft did not accompany the F-117A as was proper practice.

The most radar-reflective part of the F-117A was the flat underbelly; thus, pilots were trained not to perform banking turns in enemy airspace. The enemy was aware of the presence of this aircraft and had occasional radar returns, but not enough for a target lock.

So one day, they moved their radar directly beneath the known nightly flight path, got a lock onto the target and shot it down. Some say lock was made when it had its bomb bay doors open, providing a higher radar signature.

The wreckage was sold to the Russians and Chinese. The pilot was rescued but came close to capture.

The F-117A is now regarded as obsolete technology, and was withdrawn from service in 2008.

Fig.34: the Army's Australian Multicam Camouflage Uniform (AMCU). The pattern and colours are designed to blend into the background.

engines (not necessary for nuclear submarines). Radar absorbing coatings were first used on U-boats during WWII (along with acoustic tiles).

Noise generated by submarines is minimised by careful attention to hull design to ensure a minimum of noise-generating turbulence, plus particular attention to the propeller or propulsor design such as a pump jet. Also, internal equipment noise from devices such as pumps, fans and motors is minimised via noise and vibration-isolating mountings.

Australia's current Collins-class submarines had several noise problems when new; the solutions are documented at siliconchip.com.au/link/aazg

Hopefully, lessons have been learned, and the problems and their causes are not repeated in the new submarines under procurement.

Acoustic tiles can serve either an anechoic function (reducing the strength of reflected sonar waves) or a decoupling function (reducing the amount of internal submarine noise radiated to the outside). Ideally, a single tile system will perform both functions. Rubber tiles typically have holes or inclusions designed to scatter acoustic energy, or eliminate it by destructive interference.

The latest development in tile technology is materials known as acoustic metamaterials, and a particular design known as a phononic crystal.

Phononic crystals have a bandgap much like the bandgap in semiconductor materials, so they absorb sound over the designed frequency range. In Australia, such research is underway by the UNSW School of Mechanical and Manufacturing Engineering.

Variation of the acoustic performance of tiles with depth must be considered, as hollow cavities may be compressed due to pressure, altering the dimensions and therefore the frequency response.

Other approaches to acoustic energy management with a submarine are outlined in US Patents US5220535A "Sonar baffles" and US4450544A "Absorptive sonar baffle". However, these appear not to be known to be in service.

Other methods that can be used to find submarines and which need to be managed for stealth purposes include:

- magnetic anomaly detection, where distortions in the Earth's magnetic field caused by a submarine are detected.

Fig.35: a ghillie or yowie suit for optical stealth. The shoes are generally hidden behind the wearer's body.

- infrared detection of surfaced submarine.
- a trail of warm water left by a submarine's cooling system (especially nuclear subs).
- detection of pressure waves from a submarine.
- detection via satellite of the surface wake created by a submerged submarine.
- detection of bioluminescence caused by the excitation by a submarine of organisms such as dinoflagellates.

HyperStealth "Quantum Stealth" material

HyperStealth Biotechnology Corp (siliconchip.com.au/link/aazh) is a Canadian camouflage design company. They developed a "Quantum Stealth" optical stealth material that is as thin as paper, passive, cheap and bends light around an object to make it appear invisible or at least highly obscured under the right circumstances (Fig.32).

It uses one or more lenticular lenses, which you can sometimes buy cheaply on eBay if you want to experiment yourself. A lenticular lens is usually in the form of a flat sheet with a series of parallel long convex lenses running along its length. They are the basis of stickers and cards in which the image appears to move when you move the card or your perspective.

The HyperStealth material essentially disguises the object behind by stretching and bringing together the images from

Australian stealth materials capability

Australia has the capability to research and manufacture materials for radar stealth.

See the video *"Radar Absorbing Materials for Australian Defence Platforms, by Dr Andrew Amiet"* at siliconchip.com.au/link/aazi

Australia can also design and manufacture anechoic tiles for submarines. In both cases, materials are optimised for Australian conditions such as warm weather and water. Both research activities occur through the Defence Science and Technology Group (DST).

Supersonic anti-ship missiles – not very stealthy!

One of the advantages of a ship with a low radar signature is that it is less visible to anti-ship missiles that typically have active radar homing during the terminal phase. Other missiles use infrared homing, so a low infrared signature is important as well.

More advanced missiles also can home in on a ship's "electronic signature"; for example, the JSM mentioned above which has an RF sensor under development in Australia.

As mentioned earlier, ships rely on close-in weapons system (CIWS) to destroy incoming missiles. A supersonic missile gives the CIWS less time to react before it hits the ship. There is current controversy since Russia and China have supersonic anti-ship cruise missiles and the United States and allies only have relatively few in service.

There are several reasons for this. Faster missiles tend to fly at higher altitudes where the air is thinner, making them visible from a greater distance as compared to a sea-skimming subsonic missile.

A missile flying at 10m above the surface can be detected at 31km with a radar 20m above the surface, but a Russian Kh-32 missile with a speed of at least Mach 4.1 flies at 40,000m altitude and could theoretically be detected at a range of 843km away. This means longer-range anti-missile missiles could engage it before coming into range of the CIWS.

So a slower, lower flying missile is only detectable much later than a faster, higher-flying one. Therefore, faster missiles are not necessarily better.

For more details, see the video *"Why Does the US Not Have Supersonic ASMs? (Anti-Ship Missiles)"* at **siliconchip.com.au/link/aazj**

either side of it. The object has to be at a certain distance behind the invisibility screen for this to work.

This product has been promoted to various military organisations, but it is not clear what practical use it would have.

See the video *"Hyperstealth Invisibility Cloak 9 Minute Promotional Video"* at **siliconchip.com.au/link/aazk** and also *"Quantum Stealth (Invisibility Cloak) Edited 49 Minute Technical Edition"* at **siliconchip.com.au/link/aazl**

There is also an independent video production titled *"How this 'invisibility cloak' material is made and how it works"* at **siliconchip.com.au/link/aazm**

Fibrotex

Fibrotex (**siliconchip.com.au/link/aazn**) is an Israeli company that makes a variety of signature management products, including the mobile multi-spectral camouflage system (Fig.33), intended to be quickly applied to vehicles to reduce their signature in the optical, infrared and radar frequencies. See the video *"Mobile Camouflage – Fibrotex"* at **siliconchip.com.au/link/aazo**

Stealth clothing

The most basic and ancient method of stealth is through visual camouflage. Camouflage to blend in with the background is extensively used by animals. Similarly, people can wear colours and patterns that blend in with the background.

The current standard Australian military camouflage uniform since 2014 is the Australian MultiCam Camouflage Uniform (AMCU) – see Fig.34. The pattern is based on the US-developed Crye Precision MultiCam with a colour palette derived from the previously used Australian Disruptive Pattern Camouflage Uniform (DPCU, also known as Auscam or jelly bean camo).

The AMCU was designed by Defence Science and Technology Group and is intended to work in all areas of Australia and the immediate region. It uses a total of six colours and also takes into account its near infra-red signature. There is a variant for the Navy known as the Marine Multi-cam Pattern Uniform (MMPU).

According to the developer of the MultiCam pattern, it works by taking advantage of the way a person perceives shape, volume and colour with the brain doing a lot of "filling in" for the eye. This effect is exploited to trick the brain into seeing the MultiCam pattern as part of the background, rather than as a distinct object.

A ghillie suit (or yowie suit as it is known in the Australian Army – see Fig.35) is a type of optical stealth clothing often worn by military snipers (but also by wildlife photographers and hunters). It is designed to blend in with a particular environment. Such suits are hand-made, often by the snipers themselves. They are effective but can be hot and heavy.

Military clothing is usually designed for relatively low optical visibility in its intended operating environment, but maintaining low visibility to radar and infrared is also increasingly important. This requires so-called multispectral camouflage.

NIR compliance refers to clothing and vehicles that have been treated to make them less visible in the near-infrared (NIR), making them less visible to night vision devices (NVDs). These typically operate in the visible and near-infrared range (wavelengths of 0.4-1.0μm) while thermal infrared imaging cameras typically operate in the range of 3-12μm (see Fig.36). So NIR compliance does not give protection against thermal imaging systems.

The Russian Ratnik combat clothing, as well as the military uniforms of some other countries, is made of materials that render it less visible to infrared imaging systems.

In 2013, Artist Adam Harvey developed a line of street clothing which renders the wearer less visible to the thermal infrared cameras of surveillance drones. The items were said to be made from silver-plated fabric which reflected thermal radiation. They do not seem to be available at the moment. See **siliconchip.com.au/link/aazp**

Fig.36: this Phoenix-H Handheld Thermal Imaging Surveillance Sight can spot vehicles with unsuppressed infrared signatures at up to 11km or people up to 6km. It operates in the 3μm-5μm range.

New B-21 "Raider" stealth bomber details revealed

The US Air Force has been working on a new long-range conventional/nuclear stealth bomber for some time now. It will be known as the B-21 Raider, with a planned first flight in December 2021.

It will re-use some existing technology and parts, such as the engines from the F-35 stealth fighter; the idea is to use established technology where applicable rather than developing new technologies. It will also use an "open architecture" with its electronics and software, making it much easier and cheaper to upgrade, to cope with new operational conditions and new requirements.

All these features will supposedly help keep costs down, with an estimated cost of around US$550 million per aircraft (in 2010 dollars). That is about half the cost of the B-2 bomber it is intended to replace, and only about 30% more than a wide-body commercial jet like the Boeing 777-9.

The Northrop Grumman B-21 will join the current heavy bomber fleet which consists of Boeing B-52s (entered service in 1955, planned retirement in 2050), the Rockwell B-1B (entered service in 1985, planned retirement in 2036) and Northrop Grumman B-2 (entered service in 1993).

It will supposedly be able to "destroy any target, anywhere", including deeply buried targets. It will ultimately replace the B-2 in the strategic nuclear role, and the B-1B for conventional bombing.

The B-21 will also have the capability to operate without external communications, which might be unavailable during wartime due to jamming or nuclear strikes. Their use might also reveal the location of the aircraft.

The B-21 is designed with low maintenance requirements. The B-2 bomber requires a lot of maintenance, primarily due to its stealth coatings.

One design requirement for the B-21 was that it should be as easy to maintain as a conventional F-15 fighter jet.

The B-21 is similar to the original B-2 bomber concept, before its design was altered late in its development. The B-2 was initially conceived as a high-altitude bomber, but it was later decided that it needed low-altitude flight capability to evade the then-newly developed Soviet radars.

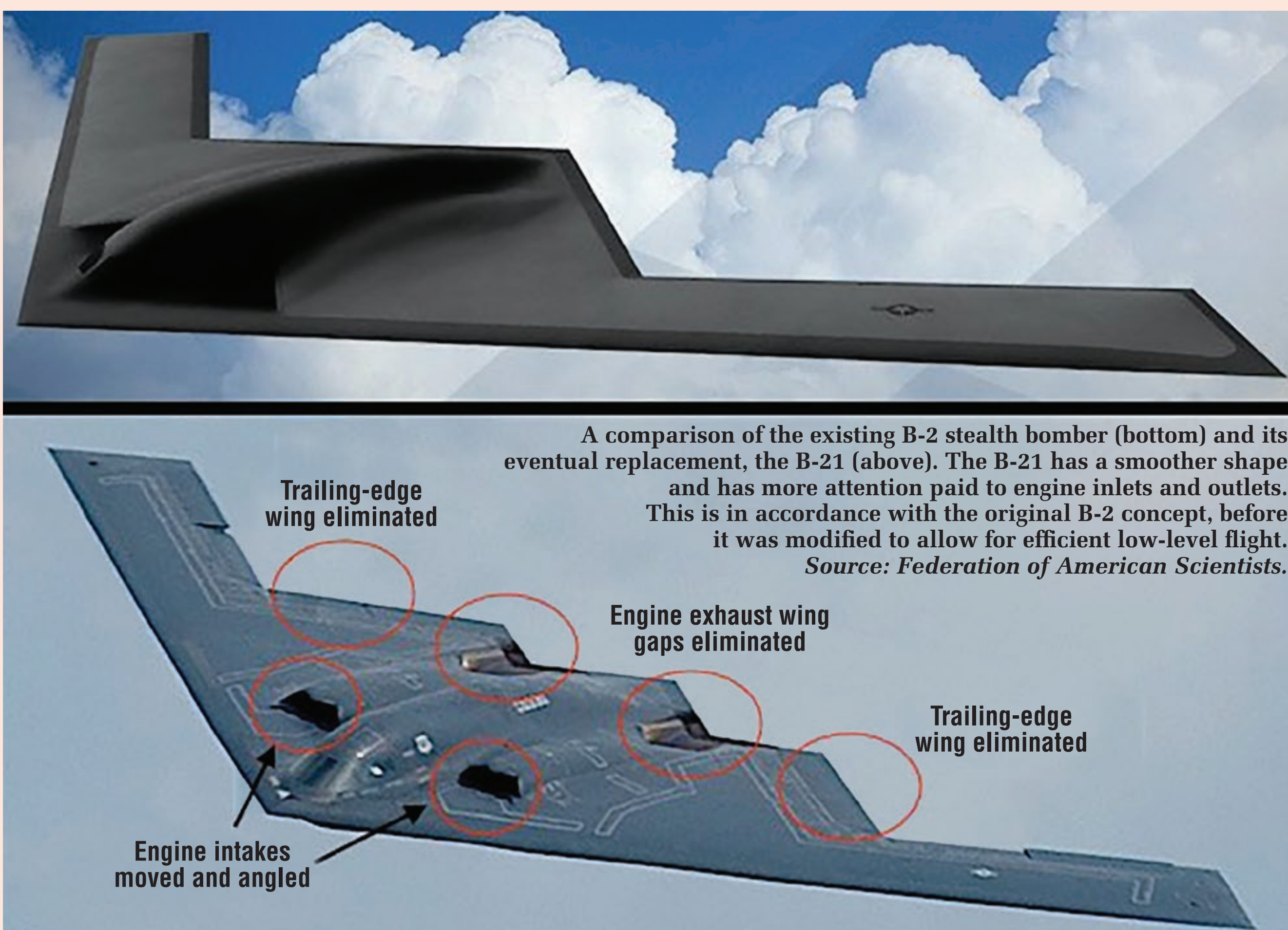
This caused a reduction in range and payload, and resulted in a larger radar cross-section (RCS).

The B-21 is also designed to be more stealthy in the lower-frequency VHF and UHF bands; increasingly, radar systems are designed to operate at these frequencies to detect stealth aircraft (which are typically designed to evade higher-frequency radar).

The B-21 will supposedly be so invisible to radar at typical illumination angles that it will blend in with the background noise, even in the VHF and UHF bands.

To achieve stealth at lower frequencies from shaping alone, geometric aircraft features have to be longer than the wavelength of the radar, or else electrical resonance occurs, resulting in a strong signal return.

Radar absorbing materials to deal with such low frequencies would have to be of an impractical thickness, for example, as much as 60cm thick. **SC**



A comparison of the existing B-2 stealth bomber (bottom) and its eventual replacement, the B-21 (above). The B-21 has a smoother shape and has more attention paid to engine inlets and outlets. This is in accordance with the original B-2 concept, before it was modified to allow for efficient low-level flight. *Source: Federation of American Scientists.*