STATE OF STEALTH

Hunting for Heat

Infrared low-observability in theory and practice

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FIFTH IN A SERIES

STATE OF STEALTH

The advent of stealth aircraft has driven nations East and West to pursue a number of counterstealth technologies. One approach has been to go lower in the electromagnetic (EM) spectrum than conventional radar frequencies, to the L, UHF, VHF and even HF radar bands.

The other promising approach is to go higher, to the infrared (IR) band where passive sensors can detect the thermal radiation that is emitted by every object, particularly hot ones such as aircraft engines, exhaust plumes and friction-heated airframes. With increasingly capable IR-guided missiles and infrared search-and-track (IRST) systems being fielded, true low observability in the future will require stealth not just in the radar bands, but in IR as well.

FLIR—TAKEN WITH AN SC8300 CAMERA

INTRODUCTION TO IR STEALTH

The IR band technically stretches from the top of the extremely high frequency (EHF) radio band at 300 GHz to the visible band starting at 430 THz, a wavelength range from 1 mm down to 0.77 µm. The usable spectrum, however, is currently limited to 0.77-14 µm, which is further divided into three sub-bands: near-IR (NIR) at 0.7-1.5 µm; mid-wavelength (MWIR) at 1.5-6.0 µm; and long-wavelength (LWIR) at 6-14 µm. The exact boundaries vary and can include a short-wavelength infrared (SWIR) region in the 0.7-3.0-µm range. IRSTs function in both MWIR and LWIR. Early anti-aircraft missiles operated in NIR, but now almost all operate in MWIR, and the wavelengths of operation continue to rise.

There are several different types of IR sensors that use materials sensitive to radiation at different wavelengths within the band. Uncooled lead sulfide (PbS) detectors operate at 2-3 µm. Cooled PbS or uncooled lead selenide (PbSe) detectors operate at 3-4 µm. Newer sensors with cooled PbSe, indium-antimony or mercury cadmium telluride (HgCdTe) detectors can operate at 4-5 µm. HgCdTe can also operate in LWIR along with microbolometers and quantum well IR photodetectors. In addition, detection ranges have benefited from the integration of focal plane arrays, with increasing numbers of detectors for higher resolution.

All objects with a temperature above absolute zero emit radiation in the IR band. As temperatures rise, total emissions increase with the fourth power of degrees Kelvin/Celsius, but they are spread across wavelengths and, with every degree increase, the emissions curve shifts to shorter wavelengths. An object at 20C (68F) radiates maximally at 9.9 µm, whereas one at 1,000C radiates maximally at 2.3 µm.

Emissions also depend on materials. A metric called "emissivity" expresses the ratio of a material's radiation at a given temperature to that of a theoretically perfect emitter called a "blackbody" with an emissivity of one. Emissivity usually does not vary with wavelength, but materials can be designed so that they do.

Temperature and emissivity determine a material's "radiance," or emissions per unit area. However, an object's "intensity"—signature strength with respect to a sensor—depends on its projected area at the sensor because a detector responds to "irradiance," or the concentration of emissions striking it. Therefore, an object's IR intensity depends on viewing angle and, because the sensor is looking out from the center of a sphere, irradiance always decreases with the square of distance.

In addition to emitting thermal radiation, aircraft can reflect emissions from the Sun, sky and ground, known as sunshine, skyshine and earthshine, respectively. Controlling IR signature requires considering both emitted and reflected radiation. Due to the law of conservation of energy, all incident radiation must be absorbed, transmitted or reflected. Emissivity always equals absorptivity, and materials are usually too thick to transmit. So if emissivity decreases, reflectivity must increase.

But radiation must arrive at a sensor to be detected. The atmosphere transmits some wavelengths less than others due to molecular absorption and specular scattering, principally by water vapor and carbon dioxide. Both become denser with pressure, and the denser the gas, the deeper and wider the "absorption band." Water vapor density also varies with temperature but is so thin above 30,000 ft. it becomes insignificant. In practice, this absorption limits detection in MWIR and LWIR to "atmospheric windows" at 2-5 and 8-14 µm and means detection ranges are always worse at lower altitudes and angles.

Finally, targets must be distinguished against any background radiation or "path radiance" between the target and sensor. Ground radiance depends on vegetation and tempera-

In this mid-wavelength infrared image of the U.S. Navy's Blue Angel F/A-18s in a low-altitude pass, note the strength of the engine plume, its reflection off the stabilator of the upper aircraft and the heating of the rear fuselage.

ture and can have greater intensity than targets. The sky's radiance increases toward the horizon and varies with time of year and latitude. A clear sky can be a difficult background against which to detect an aircraft, but clouds can both block IR radiation and reflect sunlight with intensity greater than targets. Below 3 µm, the dominant source of path radiance is sunlight scattered by aerosols, and above 3 µm, thermal emissions from the air increase to the end of the MWIR band.

A target's total IR signature level (IRSL) is the sum of the signatures of all of its components. The signature of each component is determined by the contrast between its radiance and the background and path; its projected area on the sensor; the atmospheric attenuation of the emitted wavelengths—which, together with contrast and projected area, determine the component's "contrast intensity"—and the sensor's response to those wavelengths. Therefore, the primary contributors to an aircraft's IRSL depend on viewing angle and sub-band.

In MWIR, an aircraft's IRSL is largest from behind and smallest from the front. From the rear, the signature is dominated by engine "hot parts"—the nozzle centerbody, interior walls and aft face of the low-pressure turbine. The temperatures of these components are in the range of 450-700C, as are those of nozzle and exhaust plume. This is why almost all IR-guided antiaircraft missiles operate in MWIR.

In the broader rear quarter, hot parts still contribute. So does the exhaust plume, but it is not as visible as one might think. Unlike solids, gas molecules oscillate freely, which causes them to emit and absorb energy at specific "spectral lines." Since the main products of hydrocarbon combustion—water vapor and carbon dioxide—are also in the atmosphere, plume emissions are absorbed more than other signature components. However, the high pressure and temperature of the exhaust gases broadens their emissions around carbon dioxide's absorption line at 4.2 µm, creating spikes in contrast intensity at 4.15 µm and 4.45 µm. But the atmosphere still attenuates these, particularly at lower altitudes, much faster than a smaller spike at 2.2 µm.

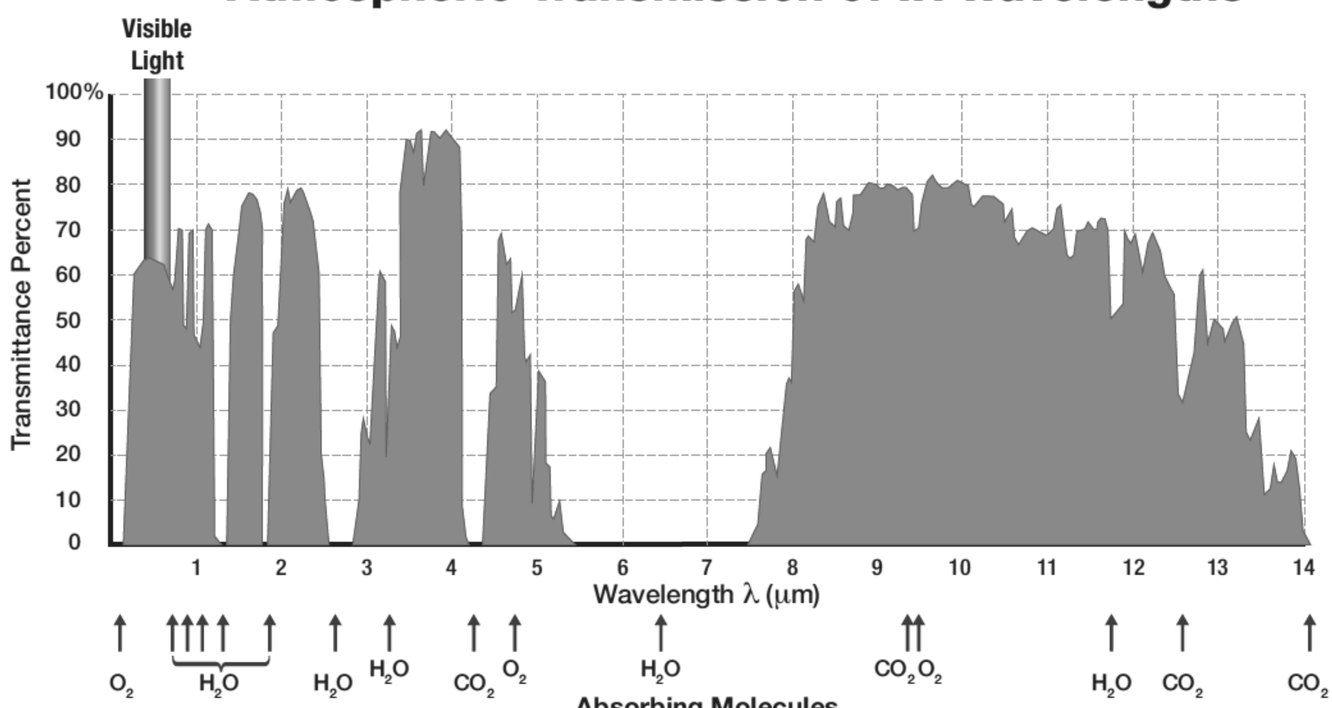
From the side, the plume's intensity is at maximum. It can extend more than 50 ft. behind the aircraft, but its radiance is concentrated in the first 4.5 ft. Side-on, the airframe also becomes a major contributor as its sensor-projected area increases. Nose-on, the leading edges of the wings and intakes are major signature contributors and the plume is still visible because it extends radially from the nozzle axis, although with rapidly decreasing temperature.

In LWIR, the greatest concern is the airframe, which can reach temperatures of 30-230C due to aerodynamic heating of the front and engine heating of the rear. While less radiant than the tailpipe, the projected area of the rear fuselage skin is 10 times larger. Reflected earthshine and skyshine are also significant in LWIR, particularly for low-emissivity surfaces and for aircraft viewed from above or below, with the earthshine's contribution growing with decreasing altitude. In NIR, reflected sunshine is the primary driver of IRSL from most angles. The plume contributes little in LWIR or NIR.

IRSL varies greatly with speed. With the engine in nonafterburning mode, the tailpipe and rear fuselage typically have larger signatures than the plume. When engaged, afterburners greatly expand the plume, double tailpipe temperatures and raise the rear fuselage temperature by about 70C. These effects can increase IRSL by almost 10 times.

The airframe, particularly its leading edges, also heats up at higher speeds. At 30,000 ft. and Mach 0.8, the skin tem-

Atmospheric Transmission of IR Wavelengths



Source: FLIR

perature might be 11% above ambient, but at Mach 1.6 it could be 44% above ambient, which can more than double detection range. And as an aircraft goes supersonic it creates a "Mach cone" of compressed, heated air that can increase the area contrasting with the background by an order of magnitude and more than double detection range.

There is no publicly available data for IRSL of modern combat aircraft and, with all the factors, there is no simple metric of detectability like radar cross-section (RCS). For benchmarking purposes, Sukhoi contends the OLS-35 MWIR IRST on its Su-35 fighter can detect an Su-30-size target at 90 km (56 mi.) from behind and 35 km from the front. But the Su-30 is a large, twin-engine aircraft without significant IR signature suppression. Theoretical texts also state IR-guided surface-to-air missiles acquire targets around 10 km away from behind.

IR suppression for an aircraft usually starts with the engine. The signatures of hot parts are most easily suppressed by masking. The plume is shrunk primarily by enhancing the mixing of exhaust air with ambient air to reduce temperature and pressure more quickly. Common techniques include increasing engine bypass ratio and injecting cooler air, water vapor or carbon particles into the exhaust. Another method is to augment nozzles with chevrons, scallops or corrugated seals to promote radial spreading of the plume and mixing with ambient air. Chevrons along the nozzle trailing edge also create shed vortices, which accelerate mixing. These augmentations reduce sound emissions as well, which is why new airliner engines are fitted with chevron exhaust nozzles. Patents filed for these nozzles cite "substantial reduction in noise and IR signature."

Skin emissions can be reduced by using low-emissivity materials. Theoretical studies have suggested reducing skin emissivity from 1 to 0 can halve detection range. Layering materials with different indices of refraction can make surfaces reflective at certain wavelengths and emissive in others, such as those with greater atmospheric attenuation. Of course, surface coatings on stealth aircraft must also consider their radar effects.

PANTHER PISS AND PLATYPUSES

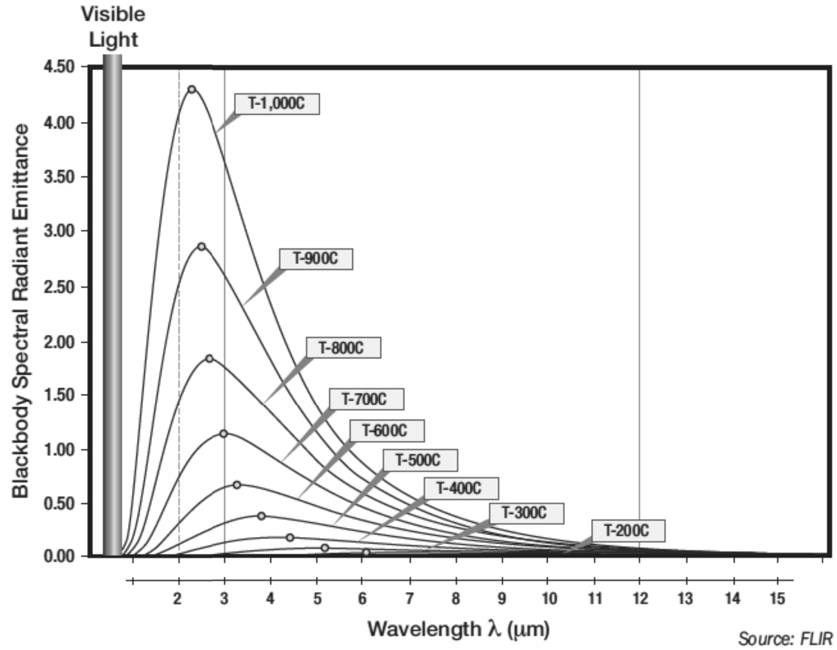
IR suppression has been part of U.S. low-observability initiatives for over a half century, often integrated with efforts to reduce rear RCS. The CIA's A-12, the first aircraft designed with signature control as a major criterion, was the first U.S. aircraft to suppress its rear RCS and reduce its vulnerability to IR-guided missiles. The aircraft's innate rear radar and IR signatures were large, due to the round, open titanium and steel nozzles and massive exhaust plumes. Lockheed compensated by adding "Panther Piss"—later revealed in declassified CIA documents to be cesium—to the fuel. This ionized the exhaust plume, reducing the aft-quadrant RCS, while also confounding IR-guided missiles of the time, possibly by radiating so intensely in NIR and MWIR that it saturated early sensors.

With the F-117, the first aircraft to use low observability as its primary means of survivability, Lockheed made IR suppression inherent to construction. The F-117's fuselage sloped aft from an apex above the cockpit to a broad, flat feature dubbed the "platypus." The engine exhaust flattened to thin slots 4-6 in. deep and 5 ft. wide, divided horizontally into a dozen or so channels. The lower fuselage terminated in a lip extending 8 in. past the exhaust at a slightly upward angle. This was covered in "heat-reflecting" tiles, similar to those used on the space shuttle, that were cooled by bypass air from the engines.

The platypus shielded the hot metal parts while the flattened plume reduced IR intensity from the side and accelerated mixing with ambient air. The extended lip masked the exhaust slot and first 8 in. of plume from below, while the low-emissivity tiles limited IR absorption and emission.

With the F-117, engineers were also introduced to the difficulty of balancing radar and IR signature suppression with the demands of extreme heat and pressure tolerance. The platypus was reportedly the hardest part of the design. Heat kept causing the structure to deform and lose its faceted outer shape. Ultimately, a structures expert designed a set of "shingled" panels that

Variation of IR Emittance with Temperature



Source: FLIR

PRATT & WHITNEY

slid over each other to accommodate thermal expansion.

Northrop's B-2 stealth bomber kept many of the IR suppression techniques of the stealth fighter. Buried deep within the flying wing, the B-2's engines are prevented from heating the outer surface. Exhaust is cooled by bypass air, including from secondary air intakes, and flattened prior to exiting over "aft deck" trenches built of titanium and covered in low-emissivity ceramic tiles. Likely containing magnetic radar-absorbent material (RAM), these extend several feet behind the nozzles, blocking the plume's core from below and the side. Also, the engine fairings and aft deck both terminate in large chevrons, which introduce shed vortices.

This aft deck has proven one of the largest drivers of maintenance cost and time on the aircraft. By the late 1990s, B-2s were experiencing exhaust lip blistering and erosion of the magnetic RAM faster than anticipated. New tiles were developed and new coatings added to the tailpipe, but cracking in the aft deck continued. By the mid-2000s, all 21 B-2s suffered from them. Interim fixes were fielded, including thermally protective covers for the tiles, while a long-term fix was developed which by 2010 was called the Third-Generation Aft Deck.

TURBINE SHIELDS AND TOPCOATS

For Lockheed's F-22 and F-35, the need for afterburning engines, supersonic flight and fighter agility, as well as the desire for less maintenance, would require some new approaches. The U.S. stealth fighters use similar IR suppression techniques for internal engine parts, tail structures and airframe coatings. They diverge most noticeably in nozzle design.

The horizontal tails of both aircraft extend well beyond the nozzles, restricting the view of the exhausts and plume core in the azimuthal plane from the side and into the rear quadrant. The engines of both also have stealthy augmenters. Aft of the low-pressure turbine are thick, curved vanes that, when looking up the tailpipe, block any direct view of the hot, rotating turbine components. Fuel injectors are integrated into these vanes, replacing the conventional afterburner spray bars and flame holders. The vanes mask the turbine and contain minute holes that introduce cooler air.

Both aircraft also feature IR-suppressive skin coatings. The final addition to the F-22's low-observable treatment is a polyurethane-based "IR topcoat" precisely sprayed by robots. Such IR topcoats have also been included in the F-16's Have Glass signature reduction program. The F-22 may also use fuel to cool its leading edges.

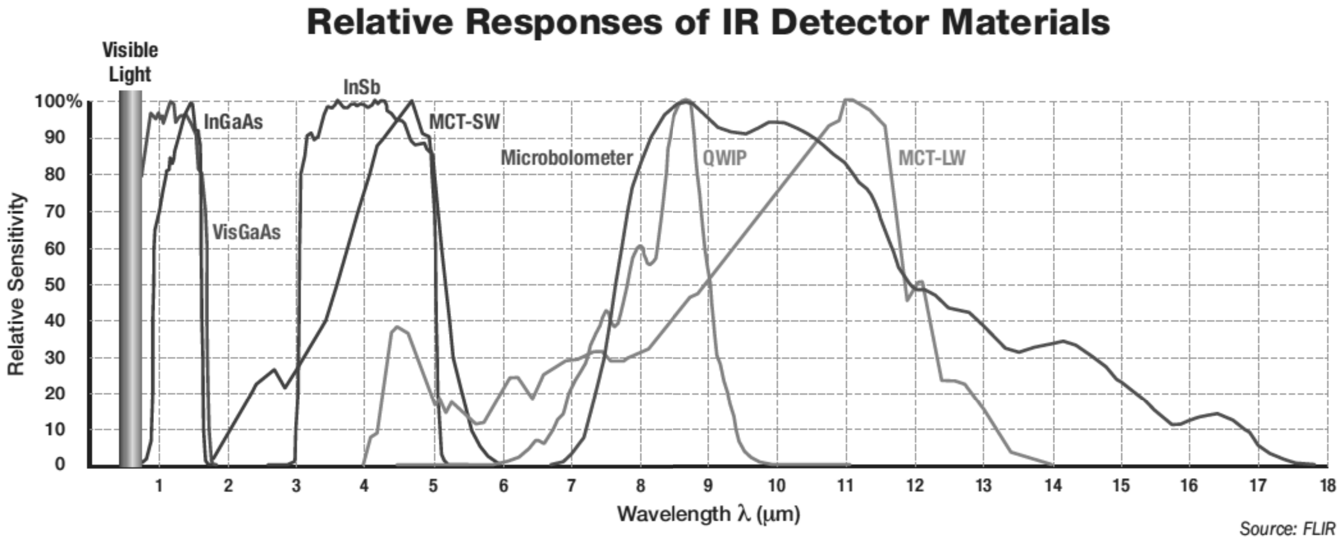
Despite the RAM fiber mats in the F-35's skin, Lockheed still finishes the aircraft with a polyurethane-based RAM coating applied by a newer robotic system. Program officials have stated this outmost layer possesses anti-friction properties; MWIR imagery of the F-35 suggests low emissivity as well. Both aircraft coatings still exhibit poor wear and temperature resistance and have needed time-intensive recoatings more frequently than desired. In 2015, the U.S. Air Force announced it was testing a new coating for the F-35 with better abrasion and temperature resistance.

The exact composition of the coatings is unknown, but polyurethane is often used as a matrix material due to its relatively high durability, adhesion and resistance to chemicals and weather. It has a natural emissivity of 0.9, but many fillers have been demonstrated to reduce the emissivity when used in composite materials. Levels as low as 0.07 have been achieved with bronze, although at the expense of higher conductivity and therefore radar reflectivity. Multilayer glass microspheres of 5-500 μm diffused at 50-70% weight can achieve low emissivity at selected wavelengths and would probably be radar-neutral. Unoxidized iron also has emissivity in the 0.16-0.28 range, and its polyurethane-matrix composites have shown emissivity below 0.5.

WEDGES AND TAIL FEATHERS

The F-22's "non-axisymmetric," or 2D, thrust-vectoring nozzles have upper and lower surfaces ending in wedges with blended central edges. These nozzles further mask the engine hot parts while flattening the exhaust plume and

In designing the nozzle of the F135 engine that powers the F-35 Joint Strike Fighter, Pratt & Whitney aimed to rival the F-22's wedge nozzles in signature while beating it on maintenance costs. The nozzle flaps incorporate minute holes to supply cooling air, like those on the F119, and overlap to create a sawtooth trailing edge, which introduces shed vortices to the exhaust and shrinks the plume. Their interior and exterior surfaces are likely composed of low-emissivity, radar-absorbent ceramics.

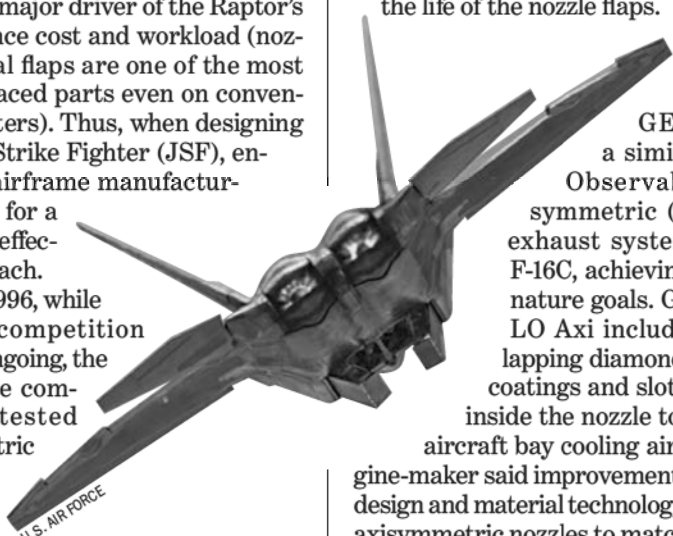


Source: FLIR

generating vortices. Minute holes are evident on their inner surfaces, likely providing bypass air for enhanced cooling.

The wedge nozzles are believed to be effective in signature reduction, but they are a major driver of the Raptor's maintenance cost and workload (nozzle internal flaps are one of the most often replaced parts even on conventional fighters). Thus, when designing the Joint Strike Fighter (JSF), engine and airframe manufacturers looked for a more cost-effective approach.

In late 1996, while the JSF competition was still ongoing, the two engine competitors tested axisymmetric designs aiming



Pratt & Whitney's F119 engines use a number of techniques to shrink their plumes and limit the IR signature of the Lockheed Martin F-22 Raptor. Just visible in this photograph are the end of the curved vanes which block direct view of the low-pressure turbine and contain minute holes that inject cooler air to the exhaust. The "wedge" nozzles also flatten the exhaust, which shortens the plume by mixing it with ambient air as well as narrowing it from the side.

to rival the wedge nozzle's signature while beating it on cost. Pratt & Whitney tested the Low-Observable Asymmetric Nozzle (LOAN) on an F-16C, which demonstrated significant reductions in RCS and IRSL. The LOAN was known to incorporate shaping, special internal and external coatings and "an advanced cooling system" that was expected to more than double the life of the nozzle flaps.

In early 1997, GE tested a similar Low-Observable Axisymmetric (LO Axi) exhaust system on an F-16C, achieving its signature goals. GE stated LO Axi included overlapping diamond shapes, coatings and slot ejectors inside the nozzle to provide aircraft bay cooling air. The engine-maker said improvements in RCS design and material technology allowed axisymmetric nozzles to match the signatures of 2D exhausts while weighing half and costing 40% as much.

The nozzle on the Pratt F135s that power the F-35 descends from these approaches. It comprises two overlapping sets of 15 flaps, offset so outer flaps are centered on the gaps between the inner flaps. The inner flaps are thin, have metallic exteriors and straight sides and terminate in inverted "Vs." The sides create rectangular gaps between them with the nozzle fully diverged.

The outer flaps, which Pratt calls "tail feathers," are thicker and covered in tiles with blended facets. They terminate in chevrons that overlap the ends of the inner flaps to create a sawtooth edge. Toward the fuselage, the tiles end in four chevrons and are covered by additional tiles that terminate fore and aft in chevrons and interlock with adjacent tiles in sawtooth-fashion.

The F135 nozzle likely suppresses IR signature through multiple methods. The trailing-edge chevrons create shed vortices, shortening the plume, while their steeper axial angle likely directs cooler ambient air into the exhaust flowpath. The inner surfaces of both sets of flaps are white and incorporate minute holes similar to those on the F119, which might supply cooling air. Some reports suggest the presence of ejectors between the tail feathers and chevrons to provide even more cooling air. The tiles and inner flap surfaces are likely composed of low emissivity, RAM composites. The trailing edge of the central fuselage also terminates in small chevrons, possibly further increasing airflow vorticity.

It is hard to quantify the success of these IR suppression efforts. Periodically, IR cameras will record stealth aircraft flying at air shows, but at ranges so close the images belie the suppressive effects of atmospheric absorption. Following the start of F-22 IR signature testing in 2000, Air Force officials stated the Raptor would exhibit a "low all-aspect IR signature under sustained supersonic conditions." Some images captured by IR-sensor manufacturer FLIR of the F-35 at the Farnborough Airshow in 2016 suggest effective suppression of engine airframe heating and nozzle emissions. Undoubtedly, IR sensors are advancing, but they are also being met with initiatives to suppress IR signature.

Gallery *See more on reducing IR signatures on the F-117, B-2, F-22 and F-35:* **AviationWeek.com/SOS-Part-5**