Joint Strike Fighter Air Quality Emissions Estimating

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INTRODUCTION

The JSF Program Office began anticipating constraints to deployment long before the manufacturer was selected and before the availability of any JSF-derived emissions data. As additional information has become available, emissions models have been continually updated and improved.

The basing of a new aircraft weapon system is probably the military action that could have the most significant effect on the environment of the community surrounding the military base. The JSF program is the largest weapon system acquisition in history, involving the purchase of over 3000 new aircraft, most of which will be based on U.S. soil, but the JSF, designated F-35, is expected to be deployed in over eight other nations.

The work to date has been focused on meeting the United States domestic Clean Air Act General Conformity requirements, but we fully anticipate a similar evaluation will be required for the deployment of the JSF at bases in the United Kingdom and at bases around the world. The purpose of this paper is to present how we are developing emissions estimates and to stimulate discussion about how air quality impact considerations are taken into account for military aircraft deployments elsewhere in the world.

CLEAN AIR ACT GENERAL CONFORMITY

The Clean Air Act (CAA) General Conformity regulations (40 CFR Part 51 Subpart W) require that the Agency responsible for the action verify that the action conforms with the State Implementation Plan (SIP) for an area that is not in attainment or in maintenance status with regards to the National Ambient Air Quality Standards (NAAQS). If an action is found to interfere with the ability of an area to reach attainment, the action is prohibited by Section 176(c) of the CAA. Interference could mean:

1. Cause or contribute to a new violation of any standard;
2. Increase the frequency or severity of any existing violation of any standard; or
3. Delay the timely attainment of any standard or other milestone in any area.

Table 1 Conformity De Minimis Thresholds (40 CFR 51.853)

Nonattainment Area Designation	Threshold (tons/year)
Ozone (O_3) Nonattainment Areas (VOCs or NO_x):	
Extreme	10
Severe	25
Serious	50
Marginal:	
VOCs	50
NO_x	100
Moderate inside an ozone transport region:	
VOCs	50
NO_x	100
Other (inc. Moderate nonattainment outside transport region)	100
Nitrogen Dioxide (NO_2) All Nonattainment Areas	100
Carbon Monoxide (CO) All Nonattainment Areas	100
Sulfur Dioxide (SO_2) All Nonattainment Areas	100
Particulate Matter (PM_{10}) Nonattainment Areas:	
Serious	70
Moderate	100
Maintenance Areas	
Lead (Pb) All Nonattainment Areas	25
Ozone Maintenance Areas (VOCs):	
Inside an ozone transport region	50
Outside an ozone transport region	100
Ozone Maintenance Areas (NO_x, SO_2, or NO_2)	100

If the action does not qualify for an exemption, then the agency must determine if the action can be excluded as a “de minimis” project. The regulation requires that the agency proposing the action to calculate the total of direct and indirect emissions for each pollutant resulting from the project. The emissions increases are compared to the de minimis levels (Table 1). If the total falls below the de minimis levels, the action is exempted from further analysis so long as it doesn’t equal or exceed 10% of the air quality control area’s emission inventory for each nonattainment pollutant.

Since aircraft deployments do not qualify for any exemptions, an estimate of the emissions is required regardless of whether the action will ultimately be considered de minimus or not.

ESTIMATING AIRCRAFT EMISSIONS

A General Conformity Analysis requires that both direct and indirect emissions be considered in the analysis.

Direct emissions include:

- Aircraft Operations,
- Refueling Operations,
- Testing and Maintenance,
- Ground Support Equipment (GSE), and
- Construction Activities

Indirect emissions include:

- Emissions associated with commuting vehicle traffic for new or temporary workers,
- Emissions from additional power generation,
- Related activity in a neighboring area, or
- New infrastructure that will be required for the action.

As the Program and propulsion system mature, the understanding of the emissions matures as well. Currently, there is not enough information to project anything but notional construction and indirect emissions. It is expected that construction emissions will most likely precede the worst-case deployment year. Since for the most part the program will be replacing existing aircraft, it is expected that there will be no net increase or decrease in indirect emissions. Similarly, the GSE requirements have not yet been established, but they will most likely be no greater than for legacy aircraft and are likely to be lower. Finally, it is not anticipated that the maintenance requirements will include engine overhaul at organic military facilities. There will be some minor maintenance in-frame engine testing, but these will be at low thrust because the aircraft is not designed to be restrained at high thrust settings.

The initial buy of the F-35 will utilize the F135 engine being developed by Pratt and Whitney (P&W). The engine is still in development and as the engine design matures so also will the emissions indexes. General Electric (GE) is also developing an engine (F136) that will be interchangeable and part of future aircraft buys. Also, as more flight time is logged on the engine, the estimates of the fuel flow and time in mode requirements will get better. The aircraft has significantly greater power than legacy aircraft so it is not reasonable to assume that the fight profile will involve the same time-in-mode and fuel flows to accomplish a landing and takeoff (LTO) cycle. Furthermore, the Short Takeoff, Vertical Landing (STOVL) version will be flown very differently than either the legacy F/A-18, F-16, or even the AV-8B (Harrier) legacy aircraft. Unlike the F/A-18 and F-16, the STOVL version can not only land and take off conventionally, but it is also capable of vertical takeoff and landings as well as rolling takeoffs and landings like the Harrier. The emissions estimates for the aircraft operations, therefore, must be developed by looking at the emissions from each portion of the LTO cycle, considering the time-in-mode, the emissions for each mode or power setting. Unlike the situation for commercial, transport and even, to some extent, traditional fighter aircraft, not all LTOs are alike because of the operational flexibility requirements. As a result traditional emission estimating tools like the US Federal Aviation Agency's (FAA's) Emissions and Dispersion Modeling System (EDMS) program are not appropriate, but the approach used to develop the emissions estimates is the same.

There are three main components that go into estimating aircraft operation emissions:
1. Engine emissions indexes from engine tests,
2. Fuel flows and times-in-mode from test pilot flights and/or simulator flights,
3. The number of each type of landing and takeoff or missions necessary per pilot per year to gain or maintain competence in the maneuver or mission type, and
4. The number of pilots per aircraft and the number of aircraft.

Engine Emissions Indexes

The emission index (EI) is defined as the pounds of emissions per thousand pounds of fuel (or gm of emissions per kg of fuel). As the engine design matures, more emissions data becomes available and the emission indexes get more accurate. Initial estimates for the F-35 were based on EIs from similar engines scaled by fuel flow rates at rated power. As demonstrator engines are built and tested, and new emissions data is made available, the EIs will be modified.

Particulate emissions measurements are difficult and very expensive to gather. The techniques used for stacks to measuring particulate matter (PM) such as EPA Method 5, involve taking multiple isokinetic samples to represent the full stack profile. Because of the high velocities, it is difficult to take isokinetic samples. The time required to take representative samples across the large exhaust duct are very time consuming and, in the case of afterburner operations, the engines are not designed to run for extended periods of time at the higher power settings. As a result of the cost and complication of taking PM measurements for legacy aircraft, they have been the most delayed data received. Traditional visible emissions techniques used for aircraft measure Smoke Number, but there is only a poor correlation between smoke number and PM measurements.

Fortunately for the F-35 aircraft, it is unlikely that PM emissions will be sufficient to trigger General Conformity thresholds; however, with the newer focus on small particles and emissions from combustion sources, new test methods will be required. Currently the International Civil Aviation Organization (ICAO) and the Society of Automotive Engineers (SAE) E-31 committee are developing a new test method for aircraft engines. The focus of the new method is to measure the particle size and number distribution rather than measuring mass directly. These methods, while better adapted to the problems associated with measuring emissions from aircraft emissions, are not necessarily equivalent to traditional stack mass measurement techniques. One difference is that these techniques are not good at measuring condensable fractions since there is cooling of the exhaust. Also, by not measuring mass directly, it may be difficult to get full acceptance of these test methods by the regulators. However, it is likely that the new methods will be the only option for measuring particulate emissions from modern high performance jet engines and the JSF Program office is expecting to use this approach.

Mission Landing and Takeoff Profiles

In general, aircraft emissions estimates are based on flight landings, takeoffs, and flight operations. Commercial aircraft show little difference between LTOs in terms of the time-in-mode, fuel flows and emissions. Military aircraft, on the other hand, perform many different types of flight missions including, carrier landing practices, strafing practices, dive-bombing practice, and in the case of the Harrier class of aircraft and the STOVL F-35 short takeoffs and vertical landings; all involving varying times spent in the mixing layer and using different times-in-mode, power settings, and fuel flow rates. Historically, records are available to accurately estimate the emissions for legacy aircraft. For a new aircraft as radically different in capabilities such as the F-35, there is no historical data. For instance the F-35 has the capability to get above the mixing layer much faster than legacy aircraft, even if it does not use the afterburner, as a result, the emissions would be greatly over estimated if the default time-in-modes were used.

Number of Landings and Takeoffs

Fighter aircraft squadrons are of two basic types: training squadrons and front line squadrons. Training squadrons spend much more time in the cockpit honing their skills, whereas front line squadrons, while spending some of their time forward deployed such as on an aircraft carrier or at an overseas base, tend only to fly to keep proficient, and therefore fly less than the training squadrons. The emissions model calculates emissions on a per aircraft basis and for each type of squadron, and then multiplies by the number of aircraft for an overall base emissions estimate for aircraft operations.

It is not accurate to assume that the JSF will have the same number of landings and takeoffs as the legacy aircraft because there will be a greater reliance on simulators in the training and maintaining skills. As a result, the emissions model for the JSF is built from the ground up, using the planned training requirements to estimate the number of landings and takeoffs.

HARRIER EMISSIONS ESTIMATES

Rather than using the F-35 as an example of how fighter aircraft emissions are developed this paper will use the Harrier because of competition sensitivities and other considerations. The Harrier, like the STOVL F-35, has many different LTO cycles and therefore provides a good example of the complexity of these models. It is also the legacy aircraft for most of the UK JSF purchases.

Engine Emissions Indexes

As part of our efforts the Navy Aircraft Environmental Support Office (AESO) performed emissions sampling tests on a single F402-RR-408A engine[1] used in the Harrier (Night Attack Version). Prior to that there was some information provided by Rolls-Royce in 1999, but it did not include the fuel flow rates or particulate measurements[2]. Relying on emissions measurements from a single engine is always problematic, but with engines in high demand, it is difficult to get engines to test, particularly for the longer duration particulate emissions measurements so we frequently must rely on single engine test data.

AESO uses a modified EPA Method 5 method to measure particulate emissions. Method 5 is an isokinetic sampling method to capture total particulate either on a dry filter or in a condensing sample chain. The method calls for taking samples orthogonally across the stack. The modification AESO made was to only measure the emissions along one axis of the exhaust rather than orthogonally along two axes, there was also difficulty finding the requisite duct diameters upstream and downstream from a source of turbulence. The US Air Force Institute for Environmental, Safety and Occupational Health Risk Analysis (AFIERA) uses a slip stream approach in the past that appears to measure lower emissions[3].

Mission Landing and Takeoff Profiles

The Harrier has three different takeoff modes (Conventional, Short and Vertical) and four different landing modes (Conventional, Slow, Rolling Vertical and Vertical). Each landing can be used with either a straight in approach or approach with a break, or circling approach. AESO conducted pilot interviews at Marine Corps Air Station (MCAS) Yuma in Arizona, and MCAS Cherry Point in North Carolina. Tables 2 and 3 present the phases involved with various landing and takeoff operations the Harrier is capable of.

The operations cover from ground level up to the top of the mixing layer assumed to be 3,000 ft or 1,000 meters above ground level. Similarly the landing time-in-modes go from the top of the mixing layer down to ground level. The actual mixing layer depends on climatic conditions and may vary from day to day and from location to location. Similarly, there may be minor differences in how aircraft are flown at different bases, for instance at some bases the pilot may be constrained to stay below the inversion layer for air traffic control purposes.

Table 2 Harrier Takeoff Modes

Flight Operation and Mode
Conventional Takeoff
Auxiliary Power Unit On
Start/Warm-Up
Unstick*
Taxi Out
Engine Run-up
Conv. Takeoff
Climbout
Short Takeoff
Auxiliary Power Unit On
Start/Warm-Up
Unstick
Taxi Out
Engine Run-up
Short Takeoff
Climbout
Vertical Takeoff
Auxiliary Power Unit On
Start/Warm-Up
Unstick
Taxi Out
Engine Run-up
Vertical Takeoff
Climbout

*"Unstick" is a quick increase in fuel flow to overcome the resting inertia.

Number of Landings and Takeoffs

The number of each type of Takeoff and Landing per aircraft per year for legacy aircraft such as the Harrier is based on tower and/or squadron records. The number of maneuvers required will be different for training squadrons than it is for front-line squadrons that are just honing their skills. Each base will be expected to support different missions so this information may depend on the mission of the base or squadron.

Table 3 Harrier Landing Modes

Flight Operation and Mode	
Conventional Straight in Landing	**Rolling Vertical Landing w/ Straight in Approach**
Approach	Approach
Conventional Landing	Approach to RVL
On Runway	Rolling Vertical Landing
Taxi to Hot Refuel	On Runway
Hot Refuel	Taxi to Hot Refuel
Unstick	Hot Refuel
Taxi in/Shut down	Unstick
Conventional Landing w/ Break	**Rolling Vertical Landing w/ Break**
Approach	Approach to Break
Break	Break
Circle	Circle
Conventional Landing	Approach to RVL
On Runway	Rolling Vertical Landing
Taxi to Hot Refuel	On Runway
Hot Refuel	Taxi to Hot Refuel
Unstick	Hot Refuel
Taxi in/Shut down	Unstick
	Taxi in/Shut down

Flight Operation and Mode	
Slow Straight in Landing	**Vertical Landing w/ Straight in Approach**
Approach	Approach
Slow Landing	Setup for VL
On Runway	Vertical Landing
Taxi to Hot Refuel	On Runway
Hot Refuel	Taxi to Hot Refuel
Unstick	Hot Refuel
Taxi in/Shut down	Unstick
Slow Landing w/ Break	Taxi in/Shut down
Approach	**Rolling Vertical Landing w/ Break**
Break	Approach to Break
Circle	Break
Slow Landing	Circle
On Runway	Setup for VL
Taxi to Hot Refuel	Vertical Landing
Hot Refuel	On Runway
Unstick	Taxi to Hot Refuel
Taxi in/Shut down	Hot Refuel
	Unstick
	Taxi in/Shut down

CONCLUSIONS

The JSF Program uses the approach discussed above, to estimate emissions for all legacy aircraft (US Navy F/A-18, US Air Force F-16 and US Marine Corps F/A-18 or AV-8B) as well as for each type of F-35 (Conventional F-35 for the US Air Force, Carrier (or CV) F-35 for the US Navy, and the STOVL F-35 for the US Marine Corps, Air Force and UK Navy). With the inclusion of testing and other direct and indirect emissions the current and expected actual emissions can be calculated. The difference between the expected emissions and the current emissions is compared with the de minimus emissions in Table 1 and with the total emissions for the air basin to determine whether the proposed project will trigger the need for offsets or contemporaneous reductions.

It is important to note that each base is different. There may be differences in the time-in-mode from one base to another because of local conditions such as temperature and ground level altitude or even air traffic control constraints. There may also be differences in the missions supported by the base. Additionally, each base will have different personnel and construction requirements.

As more information is known about the aircraft and specific bases being considered for deployment the emission estimates will continue to be modified. Some current items that are being investigated are the ground support equipment requirements and particulate emissions. There are currently no test cells that are large enough to be able to handle the airflow of the JSF and other modern-day high performance tactical aircraft. We are working with the Society of Automotive Engineers (SAE) E-31 committee exploring alternative emissions measurement techniques for measuring particulate emissions from aircraft engines.

REFERENCES

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