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SMOKE TOXICITY

Group Chair's Study

December 16, 2025

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A INCIDENT

Location: Kenner, Louisiana
Date: December 20, 2023

B SMOKE TOXICITY GROUP

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The group also appreciates the participation of Donald Sargent and Gregory Day, PhD, who retired from the Federal Aviation Administration during this investigation.

C DETAILS OF THE STUDY

1.0 Purpose

The purpose of this study was to evaluate the potential for toxic and irritant effects of smoke entering the cockpit or cabin after activation of the load reduction device (LRD) of a CFM International LEAP-1B engine on a Boeing 737-8 MAX airplane, as occurred in this incident.

For the purpose of this report, the term “smoke” is used informally to refer to air contaminants generated during an LRD activation event, and is not limited to a formal definition of smoke as visible aerosol resulting from incomplete combustion.

2.0 Methods

A group consisting of individuals with expertise in medicine, toxicology, and industrial hygiene was formed to conduct this study. The study reviewed the circumstances of the incident, information provided by Boeing and CFM International, and selected pertinent scientific literature, regulation and guidance, and National Transportation Safety Board (NTSB) reports.

There was no direct measurable evidence of the chemical composition of the smoke or the concentrations of chemicals in the cockpit air over time during the incident. Furthermore, this study did not identify any practical experimental approach by which to reliably determine the chemical composition of the smoke or the concentrations of chemicals in the cockpit or cabin air following an LRD activation event. Thus, the study was limited to characterizing the incident exposure from available information, and to examining the potential toxicity of future LRD-related smoke events from a theoretical perspective.

This study considered potential physiological effects of smoke exposure that might adversely affect safety, with particular attention to effects that might present immediate flight safety risk after LRD activation. Flight safety risk posed by opaque LRD-related smoke directly obscuring pilot vision was not within the scope of this toxicity study.

D STUDY SUMMARY

1.0 Characterization of Incident Exposure

1.1 Background

The circumstances of the incident are described in the Operational Factors Group Factual Report in the docket for this investigation. Briefly, ingestion of a large bird (beyond certification standard) by the left (number one) engine of the incident airplane (a Southwest Airlines Boeing 737-8 MAX airliner with two CFM International LEAP-1B turbofan engines) resulted in activation of the engine's LRD, which is a passive safety system designed to reduce aircraft and engine damage in the event of a significant fan imbalance. Activation of the LRD has a secondary effect of causing a substantial amount of the affected engine's oil quantity to be discharged into the core compressor upstream of the pneumatic bleed ports during or immediately after the activation event.¹

¹ Additional information about the LEAP-1B and its LRD, as well as about bird certification limits, is available in the "Powerplant System Description" in the docket for this investigation.

1.2 Relevant Systems Information

In general, most of the air in the engine's core compressor continues past the pneumatic bleed ports into the combustion chamber to be mixed with fuel, used for thrust production, and exhausted from the rear of the engine. However, under normal operation, a small portion of the air from each engine's core compressor is diverted via the pneumatic bleed ports to be used as "bleed air" that is pre-cooled before supplying the airplane's pneumatic and environmental systems.

Before entering the airplane, bleed air from each engine passes through the airplane's corresponding pressure regulating shutoff valve (PRSOV). Closing that PRSOV stops air from passing from the engine into the airplane and triggers the downstream air conditioning pack to go offline. The PRSOV will close automatically if the engine core spools down to below a certain speed. The PRSOV also will close if a pilot moves the engine start lever to cutoff, or if a pilot pulls the engine fire switch. Those pilot actions are items 3 and 4 on the Boeing 737 MAX "Engine Fire or Engine Severe Damage or Separation" checklist (severe engine damage checklist), respectively. The first five items on this checklist are included on the "B737MAX Non-Normal Quick Reference Card" (QRC), which pilots keep close at hand.²

Much of the bleed air from the left engine supplies the left air conditioning pack, where the air is further cooled and conditioned before being distributed, primarily to the cockpit. Much of the bleed air from the right engine's pneumatic bleed ports supplies the right air conditioning pack. Air from the right air conditioning pack is combined in a mix manifold with excess air from the left air conditioning pack and with recirculated cabin air that has been filtered to remove particulates; this air mixture then is distributed to the cabin.³ Electrical equipment cooling system fans also move air from the cabin to the cockpit and from the cockpit to the forward cargo compartment.

Although the right air conditioning pack does not normally supply the cockpit, in an abnormal situation with the left air conditioning pack offline, the right air conditioning pack supplies the cockpit via the mix manifold. If one air conditioning pack goes offline while the airplane is in flight with the flaps up, the other air conditioning pack will automatically regulate to a high flow mode. Additionally, a smoke removal configuration may be automatically commanded by the electrical equipment cooling system if the system detects smoke, regardless of flap setting. In a smoke removal configuration - with the operating air conditioning pack(s) in high flow mode and with the fans used to recirculate cabin air to the mix manifold turned

² A copy of the QRC is in the docket for this investigation as attachment 6 to the Operational Factors Group Factual Report.

³ Additional information about the 737-8 MAX bleed air system is available in the "Systems 737-8 Max Bleed Air Specialist's Report" in the docket for this investigation.

off – the electrical equipment cooling system’s overboard exhaust valve opens to help clear smoke from the cockpit. This valve also opens in normal flight at low differential pressure (as occurs at low altitude) or when a pilot sets a smoke removal configuration per an appropriate checklist procedure.

1.3 Incident-Specific Information

In this incident, activation of the LRD on the left engine, and the consequent release of oil into the core compressor upstream of the left engine’s pneumatic bleed ports, resulted in smoke entering the cockpit during initial climb after takeoff. The oil that was released was Eastman Turbo Oil 2380, a widely used turbine engine synthetic lubricant that is approved for use with the LEAP-1B.⁴ According to the Flight Data Recorders Specialist’s Factual Report in the docket for this investigation, after the left engine fan speed began to roll back, the left engine oil tank quantity decreased from over 16 quarts to nearly empty in about 1.5 minutes, with more than half of this decrease occurring within the first 30 seconds. Approximately 15 seconds after the left engine fan speed began to roll back, the left PRSOV was automatically commanded to close because of decreased engine core speed. Almost 2.5 minutes after the fan speed began to roll back, the left engine start lever was moved to cutoff; about half a minute after that, the left engine fire switch was pulled. These pilot actions did not change the state of the left PRSOV, nor would these actions be expected to affect the rate of smoke clearance with the left PRSOV already closed.

No cockpit voice recording was available from the incident flight. Information about the pilots’ experience of the incident is documented in “Operational Factors Attachment 1 – Incident Flight Crew Transcripts and Written Statements,” in the docket for this investigation. That document includes transcripts of the NTSB’s separate interviews of the captain (who was pilot flying) and first officer (who was pilot monitoring) conducted on January 15, 2025.

According to the captain’s interview, immediately following the bird ingestion the airplane began to shake violently. Heavy, white smoke was visible entering the cockpit maybe about 45 seconds later (after the first cockpit alarms had occurred and, as far as the captain could recall, after the first officer had pulled out the QRC and made a radio call). Once the smoke began to enter the cockpit, it did so rapidly. The captain could smell the smoke, and it had a strange smell. The captain did not recall an associated taste. He also did not recall experiencing any irritant effects, such as his eyes watering, burning of his nose or throat, or any coughing or breathing issues during the flight. The captain could not recall the amount of time that elapsed between the first appearance of smoke and the first officer calling for the donning of oxygen masks, but said it wasn’t over a minute or two (notably, this timing cannot be verified from flight data, as oxygen mask use is not a parameter captured by the flight

⁴ The safety data sheet for Eastman Turbo Oil 2380 is in the docket for this investigation as attachment 2 to this study.

data recorder). He stated the smoke started to be fairly thick before the first officer called for donning masks; the captain stated in hindsight they probably should have put the masks on quicker, but the workload was high. The captain did not recall continuing to smell the smoke after donning his full-face oxygen mask. He stated that the smoke started dissipating pretty rapidly after the engine fire switch was pulled as part of the severe engine damage checklist. By the time the airplane stopped on the runway, there was no smoke in the cockpit. The captain removed his oxygen mask before taxiing to the gate. He thought the first officer probably removed his oxygen mask around the same time; the captain stated the first officer did not remove his mask during flight.

According to the first officer's interview, the cockpit filled with smoke within about 5 seconds of the airplane beginning to shake (he did not recall if he had the QRC out before the smoke started). The smoke was very white, and had an acrid smell and taste, like burning oil. The first officer did not experience any irritation, eye watering, trouble breathing, or coughing because of the smoke, and never felt that the smoke was dangerous to him personally. He donned a full-face oxygen mask prior to performing the severe engine damage checklist called for by the captain. The first officer could not recall continuing to taste the smoke after donning his oxygen mask. At some point, the smoke began to dissipate; he did not recall exactly when this happened, or whether it was associated with a particular action by the flight crew.⁵ The first officer stated the smoke probably dissipated somewhere on the downwind leg, certainly before final approach. As far as he could recall, he believed he removed his oxygen mask when the smoke dissipated, prior to landing.

Neither the captain nor the first officer reported receiving immediate post-incident medical care. In the first officer's NTSB interview, the first officer reported no residual symptoms from his smoke exposure. In the captain's NTSB interview, the captain described no immediate symptoms. He described having a productive cough beginning about 1-2 days after the incident and lasting about 3-5 months; he said he did not seek medical attention for this issue, and it resolved. The captain also provided the NTSB with personal medical records related to a January 2025 cardiology evaluation for several brief episodes of chest discomfort that had occurred in the preceding month. This evaluation, which included electrocardiography, exercise and nuclear cardiac stress tests, echocardiography, and lung imaging (computed tomographic angiography), did not identify significant disease, although the captain was noted to become short of breath easily during his exercise stress test. In March 2025, the NTSB approached the captain (via his attorney) about voluntarily undergoing an evaluation by a pulmonologist of the captain's choosing, with the NTSB potentially covering costs of the evaluation, to further characterize his lung

⁵ In his written statement dated December 6, 2024, the first officer indicated he believed the smoke began to clear at about the time he turned the left air conditioning pack switch to off, which was item 8 on the severe engine damage checklist. Notably, flight data recorder information indicates the left air conditioning pack had already turned off, about 1 second after the PRSOV had closed; this was an expected effect of the PRSOV closing.

health and function. The captain communicated to the NTSB that he was feeling well, and he declined to undergo an evaluation by a pulmonologist.

The FAA medical certification files of the captain and first officer were reviewed as of February 11, 2025. At the time of the incident, both pilots held first-class medical certificates. For both pilots, their medical certificates had been issued via Special Issuance due to stable conditions not significant to this study. Both pilots achieved first-class medical recertification multiple times after the incident. As of December 2025, a query of the FAA's public Airmen Inquiry search page indicated that both pilots continued to hold first-class FAA medical certificates.

In summary, there was no evidence that the captain or first officer experienced impairing irritant or toxic symptoms of smoke exposure during the incident flight. After the flight, no adverse health effects of smoke exposure were conclusively identified for either pilot, with the caveat that the captain's respiratory symptoms in the months following the flight were incompletely characterized.

Several limitations exist to extrapolating the pilots' experience in this event to other LEAP-1B left LRD activation scenarios. In another scenario, the timing of PRSOV closure might be different, including because the engine core might not spool down as much or as quickly as it did in this incident, which in turn could be related to whether the LRD fully or partially activates. While the PRSOV remains open, any differences in variables such as engine core airflow might affect bleed air contaminants. Furthermore, the timing of donning oxygen masks might differ, and might involve mask/goggle combinations requiring additional donning steps compared to full-face masks. Additionally, different individuals might have different susceptibility to toxic or irritant effects. Some individuals might also have facial hair, whereas Southwest Airlines and many other airlines prohibit pilots from wearing beards, partly because of concerns that beards could interfere with the rapid donning and/or effective seal of a smoke-protective oxygen mask.⁶ Recent research has challenged the importance of those concerns for modern airline pilot oxygen masks, which use air pressure in hoses to pull the mask tight against the face; however, questions remain.⁷

⁶ Federal Aviation Administration. The Influence of Beards on Oxygen Mask Efficiency. [Advisory Circular AC 120-43](#). January 27, 1987.

⁷ French J, Wagner SD. Beard Length and the Efficacy of an Aviator Oxygen Mask. *Aerosp Med Hum Perform*. 2025;96(4):322-326. doi:10.3357/AMHP.6587.2025.

2.0 Theoretical Smoke Toxicity Risk

2.1 General Description

The actual toxicity of exposures to potentially toxic substances depends on multiple factors, including the identities and phases of the substances and the routes, magnitudes, and durations of exposure. Interactions among substances may also increase or decrease toxicity. In general, a substance will only have toxic effects if the magnitude and duration of exposure are high enough. Accordingly, this study considered the possible identities of toxicants and irritants in LRD-related smoke, as well as the exposure magnitudes and durations that might be encountered in an LRD-related smoke event, from a theoretical perspective.

LRD activation is thought to have minimal potential to result in the bleed air becoming contaminated with byproducts of oil combusted in the engine's combustion chamber. This is because the pneumatic bleed ports are positioned upstream of the combustion chamber in the engine. According to discussions with the engine manufacturer, sustained reversal of airflow direction within the engine core would be unlikely even under failure conditions. However, because the high operating pressures of the engine's compressor stages are associated with high temperatures, stray oil within the compressor stages can encounter temperatures above those at which the oil is thermally stable. As such, the oil's thermal degradation (pyrolysis) products, as well as products of the oil's possible incomplete combustion at high compressor temperatures, and constituents of the oil itself, should be considered as potential bleed air contaminants in an LRD activation event.⁸

Oil used in LEAP-1B engines must comply with SAE International Aerospace Standard AS5780 - Specification for Aero and Aero-Derived Gas Turbine Engine Lubricants. At the time of the incident, six oils (including Eastman Turbo Oil 2380, which was used on the incident flight) were specified as approved by the applicable CFM International Service Bulletin. The safety data sheet (SDS) for each specifically approved oil was reviewed.⁹ According to the SDSs, all approved oils include an organophosphate component: five contain tricresyl phosphate isomers and one contains isopropylated triphenyl phosphate. Most also contain aromatic amines such as n-phenyl-1-naphthalenamine. Eastman has chosen to include information in the SDSs for its approved oils that they emit acrid smoke and fumes when heated to decomposition, and that inhalation of thermal decomposition products may lead to

⁸ Houtzager M, Havermans J, Noort D, et al. *Characterisation of the toxicity of aviation turbine engine oils after pyrolysis (AVOIL)*. European Union Aviation Safety Agency. EASA.2015.HVP.23. February 16, 2017. https://www.easa.europa.eu/sites/default/files/dfu/EASA%20AVOIL_final%20report_final%20version_160217.pdf. Accessed October 30, 2025.

⁹ A CFM International Service Bulletin excerpt and SDSs for the six specifically approved oils are included in the docket for this investigation as attachments 1-7 to this study.

adverse effects including pulmonary edema (fluid in the lungs). ExxonMobil has chosen to include information in the SDSs for its approved oils that, in case of inhalation of decomposition products in a fire, symptoms may be delayed, and the exposed person may need to be kept under medical surveillance for 48 hours (notably, there was no engine fire in the incident event). All reviewed SDSs warn of potentially harmful or irritant combustion products such as carbon monoxide, carbon dioxide, phosphorous oxides, aldehydes, and other unidentified compounds.

Scientific literature on turbine engine oil pyrolysis describes many different thermal degradation products that may be formed, with the specific mix of chemicals being highly dependent on the particular conditions and potentially affected by whether the oil is used or new. Some categories of chemicals released after thermal degradation may include partially burnt hydrocarbon byproducts including acrolein and aldehydes (irritants and toxicants), gases resulting from combustion including carbon monoxide (a toxicant), other gases such as nitrogen oxides (irritants), and organophosphate isomers and their thermal degradation products (toxicants).^{8,10-14}

The possible thermal degradation products of turbine engine oil include irritants with water-solubilities ranging from high to low. In general, the water-solubility of irritant gases is the major factor influencing their site of action in the respiratory tract. Highly water-soluble irritants tend to act on the upper respiratory tract (nasal cavity, throat, and larynx) and may have effects within seconds, potentially beginning at relatively modest levels of exposure. Common primary physical effects are odor followed by irritation of the eyes, nose, and sometimes throat. Symptoms may include discomfort, watery eyes, runny nose, sneezing, cough, and shortness of breath. For highly water-soluble irritants, major effects on the lower respiratory tract (trachea, bronchi, and lungs) typically are limited to severe exposures. By contrast, irritants with low water-solubility act mainly on the lower respiratory tract, often producing minimal or no immediate symptoms, but sometimes resulting in delayed

¹⁰ Winder C, Balouet JC. The toxicity of commercial jet oils. *Environ Res.* 2002 Jun;89(2):146-164. doi:10.1006/enrs.2002.4346.

¹¹ Jones BW. *Aircraft Air Quality and Bleed Air Contamination Detection*. Federal Aviation Administration. DOT/FAA/TC-21/45. May 2022. <https://rosap.ntl.bts.gov/view/dot/62770>. Accessed October 30, 2025.

¹² Ortiz-Martinez K. *Chemical Analysis of Resulting Bleed Air Samples Collected from Simulated Engine Fluid Contamination Events*. Naval Air Warfare Center Aircraft Division, for the Federal Aviation Administration. DOT/FAA/AM-24/10. February 23, 2024. <https://rosap.ntl.bts.gov/view/dot/74306>. Accessed October 30, 2025.

¹³ Ortiz-Martinez K. *Chemical Analysis of Bleed Air Samples from Simulated Contamination Events: Ground-Based Aircraft Test*. Naval Air Warfare Center Aircraft Division, for the Federal Aviation Administration. DOT/FAA/AM-24/11. May 28, 2024. <https://rosap.ntl.bts.gov/view/dot/75788>. Accessed October 30, 2025.

¹⁴ Mumy KL. *Toxicological Evaluation of Chemical Compounds Identified in Air Samples Collected from Simulated Engine and Aircraft Contamination Events*. Naval Medical Research Unit Dayton, for the Federal Aviation Administration. DOT/FAA/AM-25/02. October 2024. <https://rosap.ntl.bts.gov/view/dot/79652>. Accessed October 30, 2025.

pulmonary edema (typically beginning about 6-24 hours after exposure) or other lung injury/inflammation. Irritants with moderate water solubility can produce a mixture of upper and lower respiratory tract effects. Additionally, single severe exposures to some irritant gases might lead to the development of bronchial hyperreactivity, which may persist for months or longer, with symptoms that may include cough, wheezing, and shortness of breath.¹⁵

The actual exposure to irritants in an LRD-related smoke event is unknown. Hypothetically, if pilots were to be sufficiently exposed to irritants that caused immediate symptoms, this could be distracting or otherwise impairing (for example, watery eyes and blinking interfering with vision), threatening the immediate safety of flight. If other health effects on the airplane occupants occurred due to smoke exposure, this might be a safety issue even if not a threat to the immediate safety of flight.

Existing scientific literature on health effects of fume-contaminated aircraft air does not address exposure circumstances directly comparable to LRD activation scenarios. Furthermore, although concerns have been raised about acute and chronic exposure to oil-fume-contaminated aircraft air possibly being related to a wide variety of short- and long-term health effects, ranging from neurological symptoms to cancer, studies have been limited by unavailable toxicological details, lack of systematic data collection, variability and non-specificity of reported symptoms, and other confounding factors.^{8,16} A recent large retrospective cohort study of crewmembers at a major French airline did not identify a significant association between undifferentiated fume event exposures and the prevalence of studied health conditions; a complementary prospective cohort study is ongoing.¹⁷ The FAA also continues to do work in the area of cabin air quality, with related requirements having been included in the FAA Modernization and Reform Act of 2012 and the FAA Reauthorization Acts of 2018 and 2024.¹⁸ However, this work generally has addressed exposure circumstances not directly comparable to LRD activation scenarios.

Importantly, LRD activation scenarios differ substantially from fume events or bleed air contamination scenarios involving slow or low-volume oil leakage. A larger

¹⁵ North CM, Christiani DC. Respiratory Disorders. In: Levy BS, Wegman DH, Baron SL, Sokas RK, eds. *Occupational and Environmental Health*. 7th ed. Oxford University Press; 2018:499-529.

¹⁶ Day GA. *Aircraft Cabin Bleed Air Contaminants: A Review*. Federal Aviation Administration. DOT/FAA/AM-15/20. November 2015. <https://rosap.ntl.bts.gov/view/dot/57184>. Accessed October 30, 2025.

¹⁷ Klerlein M, Dubiez L. Medical Consequences After a Fume Event in Commercial Airline Crews. *Aerosp Med Hum Perform*. 2025;96(1):12-17. doi:10.3357/AMHP.6531.2024. PMID: 39853293.

¹⁸ For additional information on FAA work related to cabin air quality, see: Federal Aviation Administration. Cabin Air Quality. FAA Newsroom. <https://www.faa.gov/newsroom/cabin-air-quality-0>. Updated September 4, 2025. Accessed October 30, 2025.

volume of oil can be released in a shorter time during or immediately after LRD activation. What this means for the severity of bleed air contamination is not entirely clear. On one hand, a larger amount of oil released rapidly might mean higher peak concentrations of air contaminants inside the airplane. On the other hand, such a rapid, high-volume release might lead to a substantial portion of the released oil passing out of the engine or coating engine surfaces without significantly contributing to bleed air contamination, given the fluid properties of the oil and the small portion of air from the engine core flow that is used for bleed air. Additionally, the specific chemical profiles of oil degradation products formed under the particular conditions of LRD activation (rapid oil release into a damaged engine) are unknown.

Also importantly, several factors in LRD activation scenarios would be expected to limit smoke exposures to shorter durations than those commonly addressed in toxicological literature. Exhaustion of the engine's oil supply limits the duration of oil release regardless of any automatic process or pilot action. PRSOV closure for any reason stops new contaminated air from entering the airplane from the engine and disables the associated air conditioning pack. Donning smoke-protective oxygen masks limits pilots' continued respiratory exposure to contaminated air in the cockpit, and donning full-face masks or smoke-protective goggles limits pilots' continued exposure to eye irritants. Such equipment is designed to protect pilots from smoke and harmful gases, and to be donned quickly without delaying emergency duties.¹⁹

Those factors limiting exposure duration generally are likely to be protective, with several caveats. First, while the PRSOV remains open, it is possible that some air contaminants might continue to enter the airplane for a period of time even after the oil tank empties, due to residual oil in the engine. Second, automatic PRSOV closure due to the engine spooling down after being damaged cannot be relied upon to occur at a particular time. Third, pilot action to secure the damaged engine also takes time, requiring pilots to recognize the situation and execute a checklist under conditions of high workload, decreased visibility, increased vibration, and encumbered communication, without making the critical mistake of shutting down the wrong engine. Fourth, although smoke-protective oxygen masks and goggles are readily available and designed for fast donning, and donning masks and goggles are above-the-line memory items on the Boeing 737 Max "Smoke, Fire, or Fumes" checklist, timely donning of smoke protection depends on smoke or fumes being

¹⁹ FAA airworthiness standards for transport category airplanes require that built-in smoke-protective breathing equipment be installed for the use of the flight crew ([14 CFR 25.1439\(a\)](#)), and FAA regulations for scheduled domestic airline operations require that smoke-protective breathing equipment be conveniently located on the flight deck and easily accessible for immediate use by each required flight crewmember at his or her assigned duty station ([14 CFR 121.337\(b\)\(8\)](#)). Flight crewmember protective breathing equipment must provide eye, nose, and mouth protection from toxic fumes, harmful gases, and smoke, and should be capable of being donned within 15 seconds ([14 CFR 25.1439\(b\)](#) and [TSO-C99a](#)). FAA oxygen equipment standards for transport category airplanes also require that each flight crewmember on duty in the cockpit be provided with a quick-donning-type oxygen mask that must be immediately available at the flight crewmember's station, and installed so that it can be properly donned with one hand within 5 seconds, without delaying emergency duties ([14 CFR 25.1447\(c\)\(2\)](#)).

readily detectable, and on the pilots' ability to attend to donning smoke protection while maintaining airplane control under high-workload, high-stress conditions.²⁰ In this incident, the pilots' interviews indicate that the detectability of the smoke may not have been a problem, but that the high workload during the critical phase of flight may have been a factor affecting how quickly they donned their full-face oxygen masks. Fifth, some exposure to chemicals in LRD-related smoke by non-respiratory, non-ocular routes (for example, skin or oral exposure to any chemicals that may settle onto surfaces) might persist beyond resolution of the initial smoke event, although there is no specific evidence that such exposure would pose significant risk of harm.

2.2 Boeing Computer Model of Chemicals in Cockpit Air

Following the incident, Boeing attempted to gain further insight into LRD-related smoke events through computer modeling. A report summarizing this modeling was prepared by Boeing at the NTSB's request and is in the docket for this investigation as attachment 8 to this study. As one part of this modeling, Boeing used parameters that it estimated to be reasonably conservative (favoring overstating rather than understating risk) to approximately predict concentrations of hazardous chemicals in cockpit air over time resulting from left LRD activation on a Boeing 737-8 MAX airplane with the PRSOV remaining open.

Given the lack of any direct toxicological data from an LRD-related smoke event, Boeing's model had to make significant assumptions that were based on data from other scenarios, and that could not be directly validated for an LRD activation scenario.²¹ For example, to identify the chemicals of greatest concern, Boeing used 2015 data from the National Aeronautics and Space Administration Vehicle Integrated Propulsion Research (NASA-VIPR) project, where controlled amounts of Mobil Jet Oil II (one of the oils approved for use in the LEAP-1B) were injected into the engine compressor of a C-17 military transport airplane and the resulting bleed air contaminants were measured.²² Because the rate of oil release in the incident

²⁰ A copy of the "Smoke, Fire, or Fumes" checklist is in the document "Southwest Airlines B737MAX Quick Reference Handbook [Excerpts]," in the docket for this investigation as attachment 7 to the Operational Factors Group Factual Report. The FAA also provides the following guidance in FAA Advisory Circular (AC) 120-80B: "Smoke, fire, or fumes checklists should include, as the first step, that flightcrew members don their oxygen masks and verify that the regulator is set to 100 percent. Flightcrew members should don smoke goggles and oxygen masks at the first indication of smoke or fumes and before accomplishing any abnormal or emergency procedures associated with smoke or fume elimination in accordance with company procedures, the manufacturer's recommendations, or both."

²¹ Although Boeing's assumptions could not be directly validated for an LRD activation scenario, the Boeing LRD Analysis Summary (in the docket for this investigation as attachment 8 to this study) describes how Boeing derived various assumptions and assessed the credibility of the computer model as a tool for understanding toxicity risk in an LRD activation event.

²² The SDS for Mobil Jet Oil II is in the docket for this investigation as attachment 4 to this study. For more information about NASA-VIPR, see also: Jones BW. *Aircraft Air Quality and Bleed Air Contamination Detection*. Federal Aviation Administration. DOT/FAA/TC-21/45. May 2022. <https://rosap.ntl.bts.gov/view/dot/62770>. Accessed October 30, 2025.

event was over 500 times the highest injection rate tested in NASA-VIPR, and because of differences in engine core airflow, Boeing's model scaled up the NASA-VIPR concentrations to over 4,000 times their measured values, assuming the percentage of oil taken into the bleed air system to be the same as the percentage of compressor air used for bleed air.²³ To estimate concentrations of chemicals in the cockpit over time, Boeing also made assumptions about the amount of contaminant lost in the airplane's bleed air system (line loss) due to effects such as condensation as air cools before reaching the cockpit; Boeing judged 90% line loss to be a conservative estimate. Additionally, Boeing's model relied on estimates of cockpit air volume and air exchange rate, with an assumption that smoke would distribute evenly throughout available cockpit volume, and that cockpit air exchange would continue at the rate predicted for a functioning left air conditioning pack (since the PRSOV remained open).

The computer model provided what Boeing believed to be conservative predictions (allowing for high uncertainty from the underlying major assumptions) of chemical concentrations in cockpit air over time during an LRD-related smoke event that Boeing believed represented a reasonable worst case with the PRSOV remaining open. Boeing identified formaldehyde and acrolein as the only chemicals predicted by the model to reach unsafe levels. Specifically, the concentrations of both formaldehyde and acrolein were predicted to transiently exceed 10-minute acute exposure guideline level (AEGL) values for AEGL-2 and AEGL-3 levels, before rapidly reducing again once the oil was exhausted. No other chemicals reportedly exceeded 10-minute AEGL-2 levels in Boeing's model.²⁴

AEGLs are standard levels commonly used to guide emergency response to the release of chemicals into air. AEGLs were developed for many chemicals by the National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances, established by the Environmental Protection Agency (EPA), and following formal guidance from the National Research Council.²⁵ AEGLs for a chemical are concentrations of the chemical in air at which health effects may occur in the general population, including susceptible individuals like the very young, the very old, and those with respiratory or other medical conditions.²⁶ Because of the rigorous

²³ Boeing noted that a higher scalar could exist, but assumed a core airflow from partial LRD activation resulting in continued engine operation at idle, because in such a scenario the PRSOV would not automatically close.

²⁴ According to Boeing, a small number of the chemicals included in the model did not have defined AEGL values; for those chemicals, alternative guideline values were considered. For additional information, see footnote 27.

²⁵ For more information about AEGLs and their development, see the EPA website at <https://www.epa.gov/aegl>.

²⁶ National Research Council Subcommittee on Acute Exposure Guideline Levels. Standing Operating Procedures for Developing Acute Exposure Guideline Levels for Hazardous Chemicals. National Academies Press; 2001. Available from: https://www.epa.gov/sites/default/files/2015-09/documents/sop_final_standing_operating_procedures_2001.pdf. Accessed October 30, 2025.

approach to AEGL development, and because AEGLs consider effects on susceptible subpopulations, AEGLs are widely considered to be preferred guidelines in chemical release emergencies.²⁷ AEGLs are defined for acute exposures, down to a shortest exposure duration of 10 minutes. Because of the uncertainties for very short exposure durations, no AEGL values for exposure periods of less than 10 minutes are recommended.²⁶

A 10-minute AEGL-1 corresponds to the level at which the general population, with 10 minutes of continuous exposure, could experience notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects would not be expected to be disabling and should reverse upon cessation of exposure. A 10-minute AEGL-2 corresponds to the level at which the general population, with 10 minutes of continuous exposure, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. A 10-minute AEGL-3 corresponds to the level at which the general population, with 10 minutes of continuous exposure, could experience life-threatening health effects or death. With increasing airborne concentrations above each AEGL, there is a progressive increase in the likelihood of occurrence and the severity of effects described for each corresponding AEGL. Although the AEGL values represent threshold levels for the general public, including susceptible subpopulations, some individuals with unusual responses might experience certain effects at concentrations below the corresponding AEGL.²⁶

At standard temperature and pressure, formaldehyde is a colorless, highly water-soluble gas with a pungent odor. Formaldehyde gas may cause a burning sensation of the eyes, nose, and airways. At standard temperature and pressure, acrolein is a colorless, highly water-soluble volatile liquid with an acrid odor. Acrolein vapor may cause nose, throat, and eye irritation. When formaldehyde or acrolein is inhaled, the respiratory tract is a primary site of toxic effects, and the chemicals' high water-solubility favors irritant effects on the upper respiratory tract rather than the lower respiratory tract (although both chemicals have shown potential in animal studies to damage lung tissue if inhaled for sufficient durations at very high concentrations).²⁸

²⁷ Although AEGLs are widely considered to be preferred guidelines in chemical release emergencies, numerous other short- and long-term exposure limits and guidelines have been developed for purposes of emergency response or occupational safety. Of particular note, the US Department of Energy (DOE) publishes Protective Action Criteria (PAC) for responding to uncontrolled releases of hazardous chemicals - these are 60-minute AEGL values if available; if no AEGLs are available for a chemical, the PAC use American Industrial Hygiene Association Emergency Response Planning Guidelines (ERPG) values, which are defined for 60-minute exposure durations; if no ERPG values are available, the PAC use DOE-developed Temporary Emergency Exposure Limit (TEEL) values, which also are defined for 60-minute exposure durations. Boeing took a similar approach when considering the results of its computer modeling - for the small number of chemicals that did not have defined AEGL values, Boeing considered ERPG values, and when no ERPG values were defined, Boeing considered TEEL values. However, most chemicals included in the model reportedly had available AEGL values; for these, Boeing considered 10-minute AEGL values.

²⁸ For more information about formaldehyde and acrolein, see the Agency for Toxic Substances and Disease

Boeing's initial computer model estimates after the incident were that, in an LRD activation without PRSOV closure, with assumptions Boeing thought to represent a reasonable worst case, the concentration of formaldehyde in the cockpit air could exceed the 10-minute AEGL-2 threshold (14 ppm) in 5 seconds after LRD activation and then remain above that threshold for about 4 minutes. Furthermore, the concentration of formaldehyde in the cockpit air could exceed the 10-minute AEGL-3 threshold (100 ppm) at about 39 seconds after LRD activation and then remain above that threshold for about 81 seconds, attaining a peak of just over 160 ppm.

Under the same simulation assumptions, Boeing's initial computer model estimated that the concentration of acrolein in the cockpit air could exceed the 10-minute AEGL-2 threshold (0.44 ppm) in 3 seconds after LRD activation and then remain above that threshold for just under 4.5 minutes. Furthermore, the concentration of acrolein in the cockpit air could exceed the 10-minute AEGL-3 threshold (6.2 ppm) at about 49 seconds after LRD activation and then remain above that threshold for about 61 seconds, attaining a peak of just over 8.5 ppm.

The above timeframes do not account for donning of smoke-protective equipment, which, if timely, would limit the duration of pilots' exposure to contaminated cockpit air.

Importantly, Boeing's initial simulation results do not mean that smoke exposure from an LRD activation event is lethal in 39 seconds. Rather, the computer model, using what Boeing believed to be a conservative approach to an uncertain estimation in a reasonable worst case with the PRSOV remaining open, predicted that beginning 39 seconds after LRD activation, there could be an 81-second period during which the concentrations of one or two chemicals in the cockpit air would be above 10-minute AEGL-3 levels. Again, 10-minute AEGL-3 levels are levels at which the general population, including susceptible individuals, could experience life-threatening health effects if exposed for 10 minutes. There are no established "lethal levels" for shorter-duration exposures to formaldehyde and acrolein. Regardless, Boeing took a conservative view that exposure to chemical concentrations above 10-minute AEGL-3 levels should be considered unsafe at any exposure duration, particularly given the potential for irritant effects of formaldehyde and acrolein to onset within seconds. Boeing informed the FAA about the results of the model as part of the continued operational safety program.

Boeing also adjusted its model analysis during the NTSB investigation into this incident. Boeing's latest estimates of formaldehyde and acrolein concentrations in the cockpit over time are presented in the Boeing LRD Analysis Summary in the docket

Registry (ATSDR) toxicological profile for formaldehyde (July 1999, with October 2010 addendum) at <https://wwwn.cdc.gov/TSP/ToxProfiles/ToxProfiles.aspx?id=220&tid=39>, and the ATSDR toxicological profile for acrolein (April 2025), at <https://wwwn.cdc.gov/TSP/ToxProfiles/ToxProfiles.aspx?id=557&tid=102>.

for this investigation. These estimates show lower peak concentrations and shorter durations over AEGL-3 thresholds than those discussed above, in a scenario where the PRSOV closes 60 seconds after LRD activation, due to pilot action (moving the engine start lever to cutoff or pulling the engine fire switch as part of the severe engine damage checklist). Although moving the engine start lever to cutoff or pulling the engine fire switch did not occur within 60 seconds in this incident, Boeing's estimate is in context of its subsequent flight crew operations manual bulletin/update and quick reference handbook update, which were implemented to more quickly direct flight crews to appropriate actions.

2.3 Exposure Risk to Cabin Occupants

Peak chemical concentrations in the passenger cabin following right LRD activation are expected to be substantially less than in the cockpit following left LRD activation, partly because of the substantially larger cabin air volume. Still, baseline health differences among cabin occupants might affect each occupant's individual susceptibility to smoke effects. Also, there is a potential for exposure durations to be somewhat longer for occupants in the cabin than for pilots in the cockpit, due to differences in air exchange, a lack of passenger masks designed for smoke protection, and variables affecting cabin crew donning of smoke-protective equipment.²⁹ The potential for adverse LRD-related smoke effects on individual cabin occupants therefore cannot be excluded.³⁰

Boeing's computer model, using what Boeing believed to be a conservative approach to an uncertain estimation in a reasonable worst case with the PRSOV remaining open, predicted formaldehyde and acrolein concentrations would remain below 10-minute AEGL-2 levels in the 737-8 MAX cabin after activation of the right LRD.

²⁹ FAA regulations for scheduled domestic airline operations require smoke-protective breathing equipment (PBE) units with a portable breathing gas supply to be easily accessible and conveniently located for immediate use by crewmembers in combatting fires ([14 CFR 121.337\(b\)\(9\)](#)). FAA airworthiness standards for transport category airplanes require that portable PBE units be installed for the maximum expected number of crewmembers ([14 CFR 25.1439\(a\)](#)). Portable PBE units must be able to be easily donned and to provide eye, nose, and mouth protection from toxic fumes, harmful gases, and smoke ([14 CFR 25.1439\(b\)](#) and [TSO-C116a](#)). In an LRD-related smoke event, cabin crew would first have to recognize a need to don PBE units, and then would have to access the stowed units, potentially under adverse conditions.

³⁰ The NTSB is not aware of any occupant complaints about smoke in the cabin in the incident under investigation. The NTSB also is participating as an accredited representative in the Instituto de Aeronáutica Civil de Cuba (IACC) investigation of a March 2023 event in Havana, Cuba, involving a bird strike leading to right LEAP-1B engine damage, right LRD activation, and smoke in the cabin of a Southwest Airlines Boeing 737 MAX. As of this writing, the IACC has not issued a final report for the Havana event; however, the NTSB is not aware of any associated serious injuries.

3.0 Discussion

Although there was no clear evidence of a significant toxic or irritant exposure resulting from the LRD activation on the incident flight, an LRD-related smoke event plausibly may pose toxicological risk. There are insufficient data to reliably determine the nature and magnitude of risk, particularly at what is expected to be limited exposure duration. In theory, it is reasonable to consider the potential for irritant effects on the pilots among the threats to the immediate safety of flight in an LRD-related smoke event.

Common-sense principles for minimizing exposure risk apply. Measures to reduce the likelihood, duration, and magnitude of exposure generally are protective, provided that due consideration is given to possible unintended adverse safety consequences. In NTSB Aviation Investigation Report AIR-25-03, "Mitigations Concerning Load Reduction Device Activation in CFM International LEAP-1B Engines," dated June 18, 2025, the NTSB issued safety recommendations for some protective measures, including for pilot education about actions to take in an LRD-related smoke event, and for continued development and implementation of software that detects LRD activation and automatically closes the PRSOV.³¹ This study is consistent with those recommendations.

Notably, while appropriate pilot reaction following engine damage severe enough to cause LRD activation might reduce exposure to LRD-related smoke, pilot action that occurs after LRD activation is unlikely to prevent smoke from entering the airplane. The incident demonstrated that significant smoke can enter the airplane even when the PRSOV closes approximately 15 seconds after initial engine damage. This is consistent with the fact that oil release occurs most rapidly in the seconds immediately following LRD activation – for example, in this incident, more than half the engine's oil was released in the first 30 seconds. Identifying and securing a damaged engine cannot be safely rushed. Therefore, under currently established procedures, there is a good chance that donning smoke-protective equipment will be the most effective single action pilots take to limit their personal exposure to toxicants or irritants associated with left LRD activation.

It is encouraging that, on the incident flight, with the PRSOV closing after approximately 15 seconds, neither pilot reported experiencing any toxic or irritant chemical effects that interfered with their airplane control tasks. This is consistent with the idea that software ensuring early automatic PRSOV closure could effectively mitigate smoke toxicity as a hazard to the immediate safety of flight. As long as a "false alarm" PRSOV closure is not hazardous, such a system would be most effective if biased towards closing the PRSOV as soon as possible when LRD activation is first suspected to have occurred or is predicted to be imminent.

³¹ See "Mitigations Concerning Load Reduction Device Activation in CFM International LEAP-1B Engines" in the docket for this investigation.

Presumably, any mitigation that minimizes the amount of smoke entering the airplane would minimize not only toxicity risk, but also reduction of visibility in the cockpit. Flight safety risk posed by opaque smoke directly obscuring pilot vision was outside the scope of this toxicity study and should be considered separately.

Finally, caution is advised for extrapolating this study to other engine variants equipped with similar LRDs on other airplane types (including LEAP-1A engines on Airbus A320neo airplanes and LEAP-1C engines on Commercial Aircraft Corporation of China C919 airplanes), as these were not specifically included in this study.

E LIST OF ATTACHMENTS

- Attachment 1 – Service Bulletin Excerpt with Approved Oils for CFM LEAP-1B
- Attachment 2 – Safety Data Sheet for Eastman Turbo Oil 2380
- Attachment 3 – Safety Data Sheet for Eastman Turbo Oil 2197
- Attachment 4 – Safety Data Sheet for Mobil Jet Oil II
- Attachment 5 – Safety Data Sheet for Mobil Jet Oil 254
- Attachment 6 – Safety Data Sheet for AeroShell Turbine Oil 560
- Attachment 7 – Safety Data Sheet for TURBONYCOIL 600
- Attachment 8 – Boeing LRD Analysis Summary

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