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Subject: Boeing LRD Analysis Summary - Southwest Airlines 737-8 N8830Q Left
Engine Bird Strike and Air Turnback to New Orleans, LA on December 20,
2023

Reference: Email, 23 October 2025, NTSB to Boeing, DCA24LA330 - Follow-up

Dear Mr. Banning:

In the reference e-mail, the NTSB requested a summary of Boeing's analysis performed after the subject event that involved a CFM LEAP-1B engine Load Reduction Device (LRD) activation. Enclosed is a summary of Boeing's analysis of the subject LRD activation event and a prior event that occurred in Cuba in March 2023.

Please feel free to contact us if you have any questions.

Best regards,

[REDACTED]

Stella Weidner
Director, Product Safety

Enclosure: Boeing LRD Analysis Summary - Southwest Airlines 737-8 N8830Q Left
Engine Bird Strike and Air Turnback to New Orleans, LA on December 20,
2023

cc: Dr. Turan Kayagil, MD, FACEP - Medical Officer, NTSB, Office of Research and
Engineering

Summary of Boeing Analysis of LRD Activation Events

1 System Description

1.1 737MAX Engine Bleed Air and Air Conditioning System Overview

Bleed air is drawn from either the 4th (intermediate pressure, IP) or the 10th stage (high pressure, HP) of the engine compressor to supply the airplane's environmental control system (ECS) as shown in Figure 1. The compressor stage in which it is drawn is based on the pressure demands of the system compared to the pressure being delivered by the engine (a function of engine speed). Downstream of the valves which control what stage the air is coming from is the Pressure Regulating and Shut Off Valve (PRSOV). The PRSOV is normally controlled by the Integrated Air Systems Controller (IASC) with inputs from manifold pressure and temperature sensors. When the engine bleed PRSOV closes, the engine bleed manifold pressure will be lost on the affected side, and the affected air conditioning pack flow control and shutoff valve will move to the closed position. The PRSOV can be automatically or manually commanded closed, through a relay in the Air Conditioning Accessory Unit (ACAU) for the following conditions:

- The engine spools down to < 62% N2 (minimum core speed)
- Engine start lever is moved to CUTOFF when the engine fire handle is not pulled
- The engine fire switch is pulled
- The bleed switch is selected OFF
- Bleed trip
- Dual bleed
- IASC not healthy

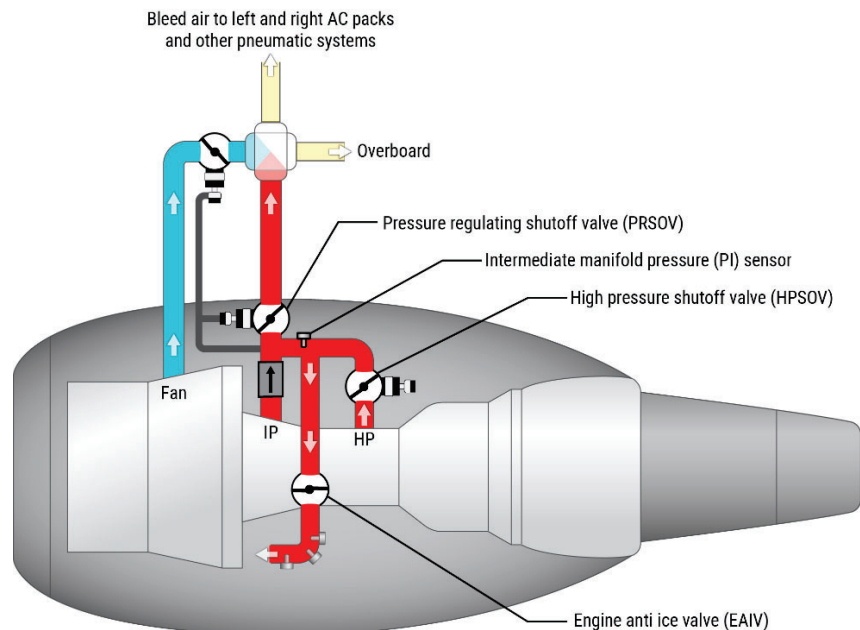


Figure 1 - Simplified engine bleed air diagram with PRSOV depicted. (Image Copyright © Boeing.)

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Downstream of the PRSOV there is an initial heat exchanger called a Precooler. This exchanger reduces the bleed air temperature from approximately 650°F (engine outlet temperature) to between 250-450°F. This air will then travel to the Environmental Control System (ECS) air conditioning packs- where the air will be cooled to meet the cooling demands of the cabin, flight deck and other compartments on the airplane.

For the majority of the cabin, this air is mixed with recirculated air at approximately a 45/55 (outside/recirc) ratio and supplied to the cabin. The flight deck receives 100% outside air from the left engine during normal operation. Air from upstream of the air conditioning pack “Trim” air is mixed with the conditioned airflow to achieve the desired temperatures for each temperature control zone on the airplane as shown in Figure 2.

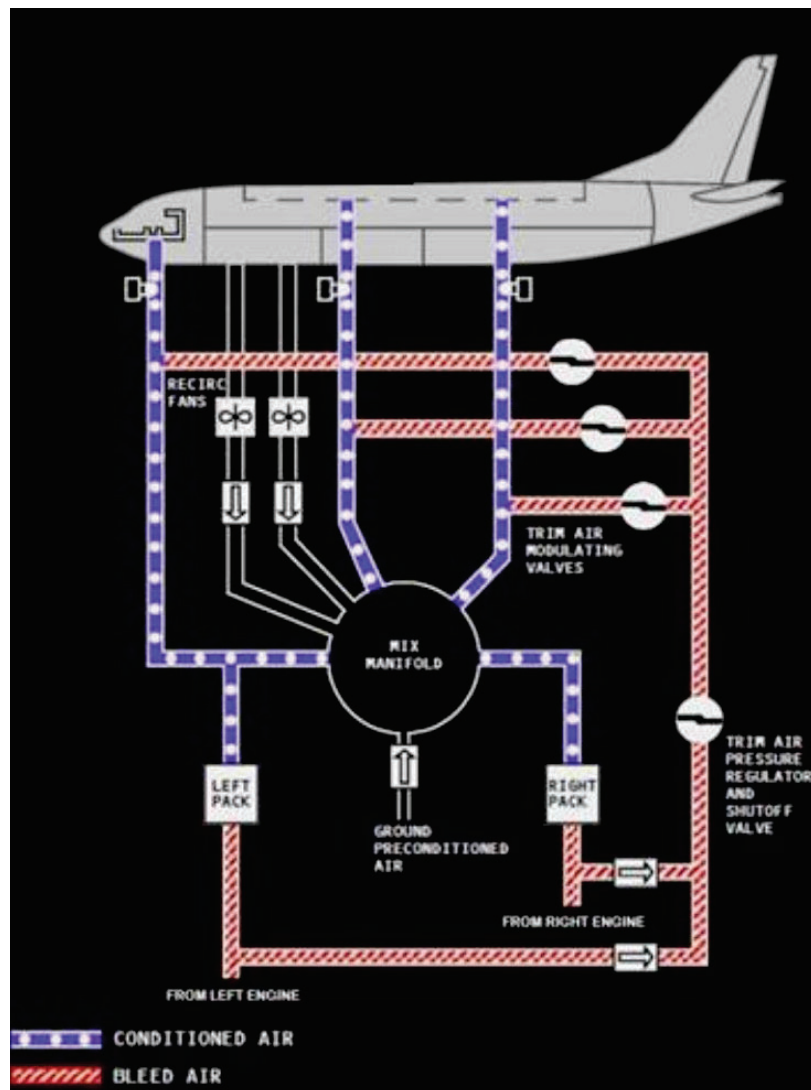


Figure 2 – Simplified Air Distribution System Overview (Image Copyright © Boeing)

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1.2 LEAP-1B Engine Load Reduction Device

Each LEAP-1B engine on the 737 MAX includes Load Reduction Device (LRD) features as shown in Figure 3. The LRD minimizes aircraft and engine damage during a fan blade failure or significant fan blade imbalance by enabling the fan to be partially mechanically disconnected from the turbomachinery, reducing the severity of the vibration transmitted from the damaged engine to the airframe. As mechanical design features, the LRD does not require pilot intervention to activate.

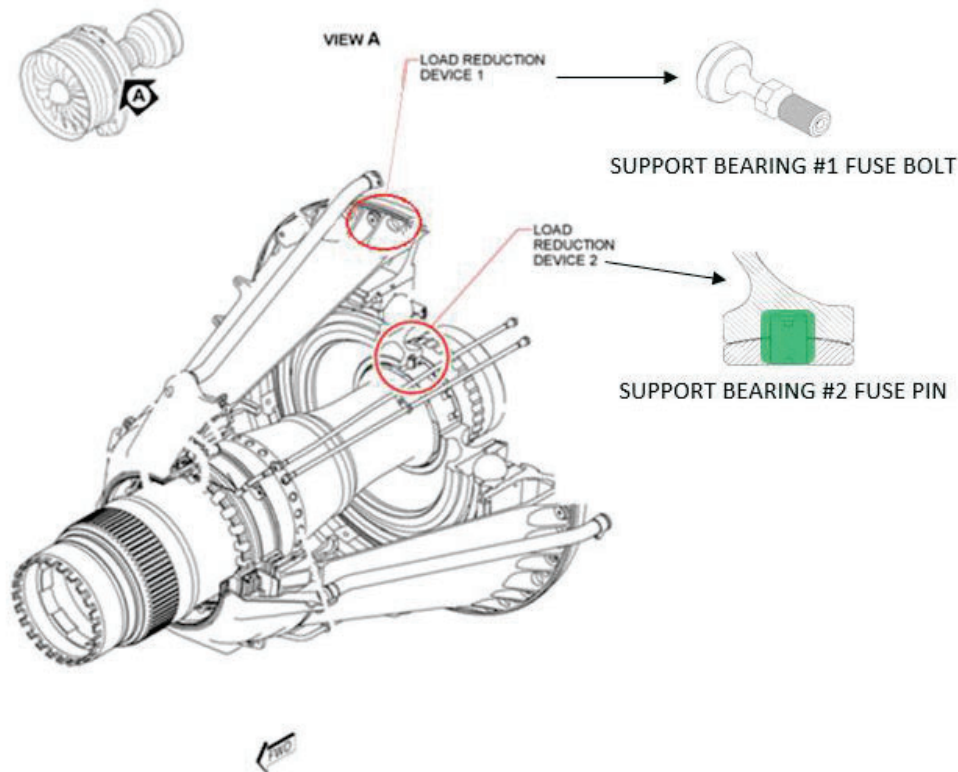


Figure 3 - The location of the LRD on the LEAP-1B engine. (Image: CFM)

2 Cuba and New Orleans Events Synopses

2.1 Initial Findings and Data Considered in Analysis

On March 5, 2023, a turkey vulture struck the number 2 (RH) engine of a 737-8 shortly after takeoff in Havana, Cuba. A single Load Reduction Device (LRD) activated within the engine and the engine continued operating under idle flow rates. During the event, oil mist entered the bleed air supply to the passenger cabin and odors were observed. Data from the Flight Data Recorder (FDR) of the 737-8 event airplane was supplied to Boeing.

On December 20, 2023, a second LRD event occurred after a bald eagle struck the number 1 (LH) engine during initial climb out of New Orleans, Louisiana. Oil mist entered the bleed air supply to the flight deck which was reported as smoke by the pilots. In this event both LRD features activated

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leaving the engine in a state where the engine spooled down and eventually shutdown. This resulted in the engine speed below 62% N2 resulting in automated closure of the PRSOV. This occurred at 16s after the bird ingestion occurred. FDR data and Continuous Engine Operational Data (CEOD) from the event flight was supplied to Boeing.

The engine core flow rate, the oil reservoir quantity, and other recorded parameters were used from both datasets for analysis in a model developed by Boeing to inform the continued operation safety program assessment of the event as described in section 3.

3 Analysis Methodology

3.1 Bleed System Concentration Modeling

3.1.1 NASA VIPR Test Background

In July of 2015, Boeing participated in a joint Vehicle Integrated Propulsion Research (VIPR) study with the Federal Aviation Administration (FAA), its Centers of Excellence for Aircraft Cabin Environmental Research (CoE ACER), the National Aeronautics and Space Administration (NASA), and the United States Air Force (USAF) where aircraft turbine oil was intentionally injected into a boroscope port of an operating engine on-board a C-17 aircraft to evaluate the byproducts produced by the passage of the oil through the engine system. Subsequent studies have verified the conclusions of the NASA VIPR study including follow-up studies with the FAA and other airline participants. NASA VIPR is the most comprehensive industry bleed air sampling campaign performed.

3.1.1.1 Chemical Compounds Assessed (46 compounds used in Boeing analysis)

The NASA VIPR study utilized standard chemical sampling measurements established by the Environmental Protection Agency (EPA) to look for a wide range of contaminants.

EPA Method TO-11A¹ is designed to look for the 13 most prevalent aldehyde compounds including formaldehyde & acetaldehyde. EPA Method TO-13A² was modified during VIPR to look specifically for organophosphate based compounds, with an emphasis on Tri-Cresyl Phosphate (TCP) due to its inclusion as an anti-wear additive in engine turbine oil. EPA method TO-15³ uses Summa Canisters to capture large volumes of air and looks for 76 individual VOCs. Finally, EPA method TO-17⁴ uses adsorbent tubes to capture other organic compounds.

Of this extensive list, 46 compounds were detected in the NASA VIPR study and were used in Boeing's analysis model for the LRD events.

3.1.1.2 Core Flow & Oil Injection Rate Scaling

To leverage the concentrations measured from the NASA VIPR study for analysis, the differences between the core flow rates (W25) from the Pratt & Whitney F117-PW-100 engine used in that study and the CFM LEAP-1B used on the 737-MAX were considered. This was represented by the equation below.

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$$[1] \text{ Engine Core Flow Rate Scalar} = \frac{W25 \text{ from NASA VIPR}}{W25 \text{ from Event}}$$

For the LRD activation cases assessed- where the engine flow rate drops quickly to idle- this equation results in a scalar value of approximately 5.78.

An additional scalar was considered based on the difference between the known injection rate in the NASA VIPR study and the leakage rate from the engine in the events as estimated from recorded data obtained from the LRD event flights.

The leakage rates for the Havana event and for the New Orleans event were estimated based on available recorded data. The scalar for each of these was determined through the following:

$$[2] \text{ Oil Injection Rate Scalar} = \frac{\text{Event Oil Leakage Rate } (\frac{g}{h})}{\text{NASA VIPR Injection Rate } (\frac{g}{h})}$$

For the Havana event the scalar value was ~712 & for the New Orleans Event the scalar value was ~1068.

The total scalar for the chemical compounds was assessed as the multiple of the core flow rate scalar and the oil injection rate scalar:

$$[3] \text{ Total Chemical Scalar} = \text{Engine Core Flow Rate Scalar} * \text{Oil Injection Rate Scalar}$$

For the Havana event this was approximately ~4122, and for the New Orleans event this was approximately ~6183.

3.1.1.3 Oil Proportion in Core Flow

Concentrations of oil within the core flow of the engine after an LRD activation are conservatively assumed to be uniform and instantaneously well mixed. The resulting concentration of any bleed air is considered equivalent in concentration to the concentration in the core flow of the engine.

3.1.1.4 Line Loss Assessment

In order to reach the cabin and flight deck, oil that passes through the engine compressor bleed port, must pass through an arduous path of system components. While not an exhaustive list, this path requires the oil to first pass through the precooler, then a complex pathway of ducting, and the respective air conditioning pack with multiple heat exchangers. The drop in oil concentration from the bleed port to a modeling point within the cabin or flight deck is called line loss.

$$[4] \text{ Line Loss} = 1 - \frac{\text{Cabin or FD Concentration}}{\text{Concentration in Core Flow of Engine}}$$

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The line loss for the LRD events assessed was based on several studies noted below that Boeing participated in where oil was intentionally injected into either an operating engine or an APU. The NASA VIPR study took PUF/XAD samples in bleed air sourced from a C-17 aircraft using EPA Method TO-13A and compared the concentrations measured at the simulated cabin from that study to the injection rate. The NASA VIPR study reported this line loss to be 90%, meaning that 90% of the oil remained in the system components and did not arrive at the sample point.

This line loss estimation was validated through a test performed by Boeing with an airline partner and industry participant where oil was intentionally injected into the APU of a 757 airplane in multiple conditions. The concentration of oil was measured in this study through EPA Method TO-13A and the line loss was calculated to be between 90% and 97% depending on the condition measured. Further validation including analysis of results from testing performed with the FAA, US NAVAIR & Kansas State University at the FAA site in Atlantic City supports the conclusion that line loss may range between 90-97%⁵.

The model developed for the LRD events uses an uncertainty analysis to account for the differences in concentrations utilized in the studies above that are below the concentrations modeled for the LRD events. The analysis was performed using both 90% and 97% line losses to account for this uncertainty. Review of a mobile phone video from the passenger cabin of Havana event from public media sources and initial pilot reports from NTSB interviews of the New Orleans event pilots were also considered as sensitivities for the line loss assessment.

3.2 Flight Deck and Cabin Concentrations Modeling

3.2.1 Air Exchange Rates

Air Exchange Rates for the 737MAX used for the LRD model were assessed using an outdoor air exchange rate in the flight deck of approximately 1 per minute. The total air exchange rate in the cabin is approximately 37 air changes per hour (ACH), with an approximate 45/55 outside airflow/recirculated airflow split. This results in a contaminated air exchange rate for the cabin of 8.325 ACH considered in the model analysis.

The analysis used to model the concentration in the flight deck was based on the concentration in the core flow of the engine and the peak concentration in the flight deck once the source of contamination is removed. This is estimated through the line loss approach above and using a contaminated air exchange rate for the flight deck of approximately 60 ACH.

The peak concentration is based on the time in which the source is removed. The model considers when the PRSOV closes which occurred at $t=16s$ in the case of the New Orleans event, or when the engine oil reservoir quantity is depleted, which occurred at $t \sim 90s$ in the case of the Havana event.

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The cabin concentration for the New Orleans event is modeled in a similar fashion considering recirculated air that is initially uncontaminated and the second AC pack being continually uncontaminated.

Similar to the flight deck, the peak concentration in the cabin is based on the time in which the source is removed. The concentration at any time after the peak concentration is determined considering the residence time of the uncontaminated air source from the opposite side AC pack.

3.2.2 AEGL Threshold Assessment Methodology

Acute Exposure Guidelines (AEGLs)⁶ are exposure limits for the general public developed by the Environmental Protection Agency (EPA). They are published in different duration periods between 10 minutes and 8 hours and three different threshold levels. For the LRD event model, 10-minute exposure limits are used as conservative toxicological practice dictates for exposures less than 10 minutes.

There are three levels for AEGLs. AEGL-1 is described by the EPA as the “airborne concentration where the general population, including susceptible individuals, could experience notable discomfort, irritation or certain asymptomatic, nonsensory effects. However, these effects are not disabling and are transient and reversible upon cessation of exposure”. AEGL-2 is described by the EPA as the airborne concentration above which it is predicted that the same population “could experience irreversible or other serious, long-lasting, adverse health effects or an impaired ability to escape.” AEGL-3 is described by the EPA as the airborne concentration where people “could experience life-threatening adverse health effects or death”-with increasing lethality potential assumed at higher concentrations and higher durations.

For the LRD model concentrations above AEGL-1 but below AEGL-2 are considered to be irritating. The effects of exposure above AEGL-2 level depends on the concentration and durations of exposure; higher concentration/duration levels are assumed to be more hazardous than lower concentrations/shorter durations. Concentrations above AEGL-3 are considered to be unsafe.

For some compounds analyzed, some effects above thresholds may take effect as soon as the concentration is reached. The ten-minute limit is used because it is the shortest exposure limit assessed in published EPA guidance, but it may not be necessary for a full ten minutes of exposure to occur for the full effect to occur.

3.2.3 Flight Deck Visibility Analysis Methodology

To correlate visibility distance and concentration Boeing leveraged fog oil as a baseline due to its similarities to engine turbine oils. The National Research Council’s Toxicity of Military Smokes & Obscurants⁷ provides a correlation between visibility and fog oil concentration. The distance is classified as 10% transmission per the Beer-Lambert Law and this was assumed in the LRD event analysis modeling.

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4 Analysis Results

4.1 Cabin Concentration (showed no compounds above AEGL-2)

Cabin concentrations for all chemicals were estimated and peak concentrations were compared to AEGL-2 thresholds. Using the more conservative 90% line loss estimate, no compounds exceed AEGL-2.

4.2 Flight Deck Concentration

Flight deck concentrations for all chemicals were estimated, and peak concentrations were compared to AEGL-2 and AEGL-3 thresholds. Two compounds, Formaldehyde and Acrolein, were found to briefly exceed AEGL-3 10-minute thresholds when assessed against the more conservative 90% line loss uncertainty for certain PRSOV closure times. The figures below show the model concentration results for these compounds with continued engine operation after an LRD activation and the effects of the 90% and 97% line loss uncertainty.

The results were used to assess the concentrations that might have been experienced by the pilots assuming an expected pilot response time of 60 seconds after an LRD event for PRSOV closure (engine start lever to cutoff or fire switch pulled) when executing the Engine Severe Damage Checklist. This assessment also considered the time for each pilot to don oxygen masks (both single and two-piece smoke goggle configurations) and conservatively assumed 60 seconds in the worst-case scenario (two-piece masks, Capt/FO sequential donning). Based upon the model analysis and assessments shown below, Boeing conservatively concluded that the second pilot, who dons their oxygen mask last, may be at risk of a potential non-incapacitating injury. While this would not prevent the flight crew from maintaining safe operation of the aircraft, Boeing conservatively determined this to be a safety issue. Boeing informed the FAA and provided assessments to the FAA as part of the continued operational safety program with the FAA prior to initiation of the NTSB investigation into the New Orleans event. After the NTSB investigation was initiated, further refinement of the model analysis was conducted based upon information received from the investigation such as pilot interviews as described in section 4.3.

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4.2.1 Formaldehyde

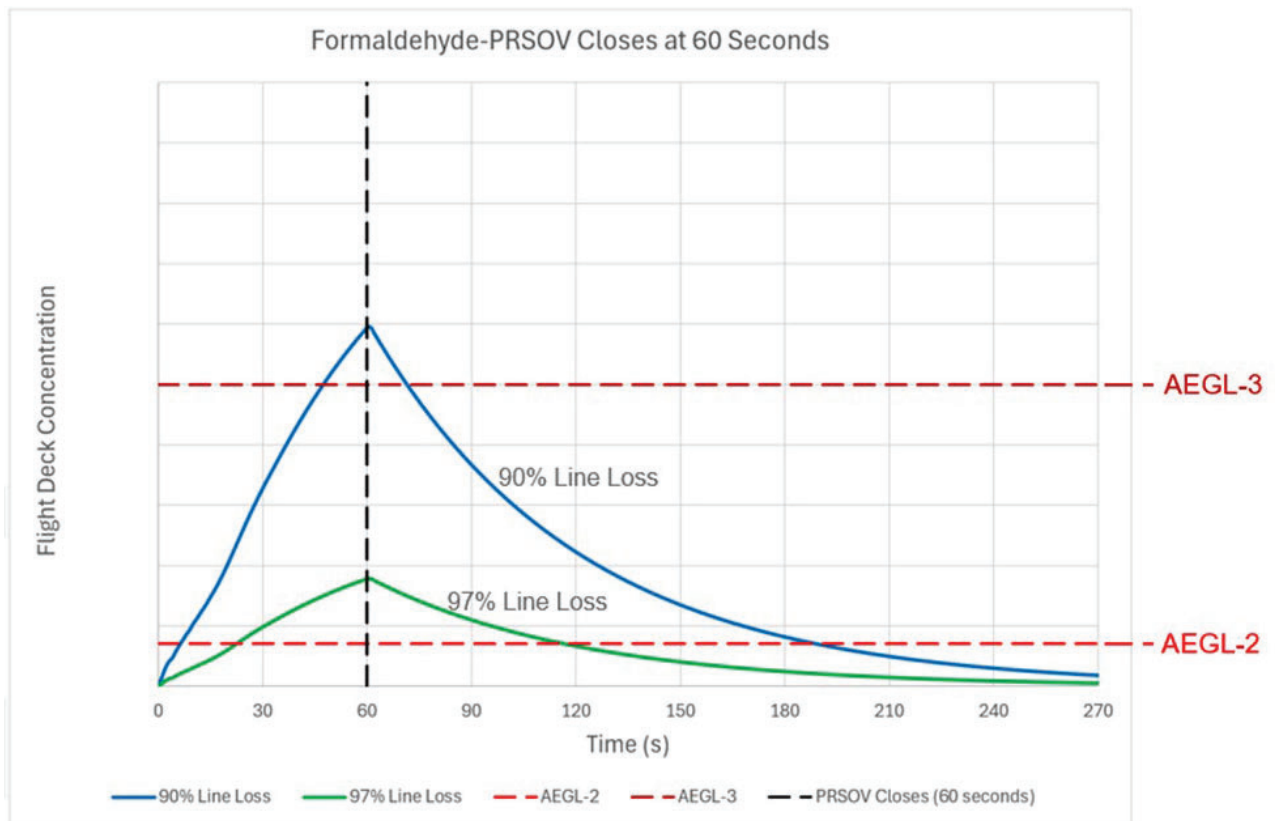
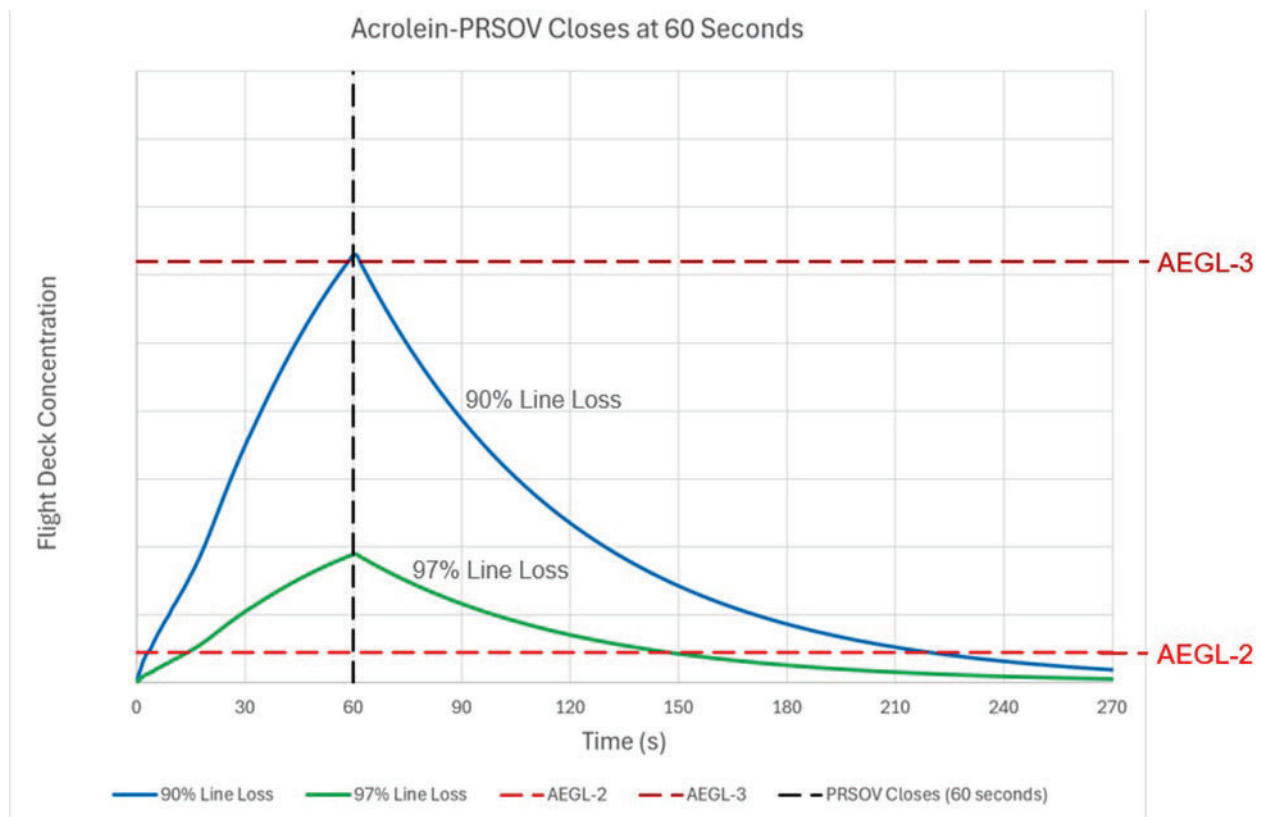


Figure 4 - Formaldehyde Concentration in Flight Deck, PRSOV Closes $t=60s$

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4.2.2 Acrolein



4.3 Flight Deck Visibility

The flight deck visibility was assessed and correlated with visibility descriptions from the New Orleans event flight crew, and passenger video from the Havana event. Sensitivity assessments were performed when descriptions from the flight crew of the New Orleans event were made available to Boeing through the continued operational safety program review and NTSB investigation. The visibility described in these descriptions were compared with analysis results and showed that the modeling methods were conservative.

5 Conclusions

Boeing's modeling methods predict contaminant concentrations and effects of LRD activations for the 737MAX given the multiple uncertainties surrounding the inputs. These inputs correlate with the visibility observed and described by the pilots of the New Orleans event. The results were utilized by Boeing to assess the events as a safety issue and to inform the FAA for their consideration as part of the continued operational safety program.

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6 References

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