AIRCRAFT OZONE CONVERTER FIELD DEACTIVATION STUDY:

CATALYST DEACTIVATION DRIVERS AND FIELD DEACTIVATION TRENDS

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Catalyst Deactivation Drivers and Field Deactivation Trends

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Aircraft Ozone Converter Field Deactivation Study: Catalyst Deactivation Drivers and Field Deactivation Trends

Executive Summary

BASF Corporation, an OEM and MRO service provider for aircraft ozone and ozone/VOC converters, has conducted a data mining and analytics study to assess catalyst deactivation drivers and field deactivation trends for ozone and ozone/VOC converters installed in long range commercial aircraft. The current practice of describing converter performance in this application defines a constraint line as a function of flight hours that bounds the performance of a predefined percentage of field returned converters. This practice is conservative in ensuring minimum ozone conversion for most of the converter population, but it does not discern natural sub-populations within the field data set that may relate to fundamental mechanisms of catalyst aging associated with distinctions among operating environments.

As a catalyst technology developer and manufacturer, BASF has studied the field aging of ozone and ozone/VOC converters and discerned its predominant deactivation mechanisms in the application. In most cases, catalyst in ozone and ozone/VOC converters deactivate due to the progressive accumulation of contaminants, which may be sourced, for example, from lubricating oils, hydraulic fluids, and/or de-icing agents that have leaked into the bleed air stream. Contaminants may penetrate deep enough into the washcoat pore structure to plug pores and restrict access to underlying active components. This results in catalyst deactivation and loss of ozone conversion performance. The BASF MRO service and wash process removes significant catalyst contamination and restores access to active components in a manner that preserves the original catalyst design. This enables a detailed converter performance history to be accrued during regular service and compared to the original design baseline.

BASF has developed a metric based on irrecoverable catalyst deactivation assessed by performance measurements before and after the BASF MRO service and wash procedure to quantify the relative aging of the catalyst. The metric tracks flight hours in a consistent fashion, reducing scatter in the data set, and thus affirms differentiation in the serviced converter population. Airline identity becomes a ready surrogate for those application variables, like aircraft maintenance and primary flight routes, that may describe significant sources of catalyst contaminants. Differentiation of converter field performance, supported by BASF performance metric data analysis, may yield hidden value to an airline in optimization of converter service life and maintenance schedules.

Aircraft Ozone Converter Field Deactivation Study:
Catalyst Deactivation Drivers and Field Deactivation Trends

I. Introduction

BASF Corporation, an OEM and MRO service provider for aircraft ozone and ozone/VOC converters, has conducted a data mining and analytics study to assess catalyst deactivation drivers and field deactivation trends for ozone and ozone/VOC converters installed in long range commercial aircraft. The study focused on converters returned for MRO service during a three-year period. BASF has developed a metric by which field deactivation trends of converter populations may be compared in a manner that is consistent with fundamental drivers of catalyst activity loss. This white paper presents insights gathered from these comparisons with a special focus on identifying strong differentiators of ozone and ozone/VOC converter field performance and their implications on aircraft maintenance.

II. Catalyst Architecture

BASF designs and manufactures the ozone decomposition catalyst and ozone/VOC decomposition/oxidation catalyst it incorporates into its OEM converter products. It is instructive to review the fundamental components of a heterogeneous catalyst as it lends insight into the data mining and analytics presented later in this paper.

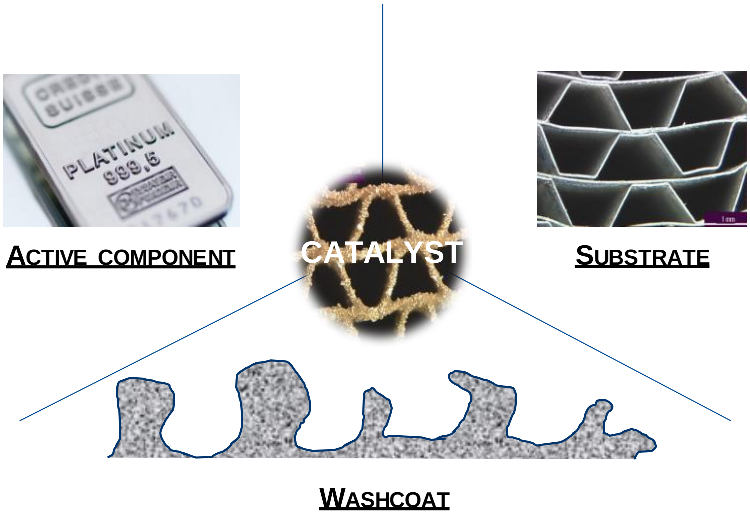

Figure 1. Heterogeneous catalyst architecture

As shown in Figure 1, a heterogeneous catalyst is composed of three main sub-components: a substrate, a washcoat, and an active component. The substrate is a metal (or ceramic) flow-through honeycomb monolith that provides mechanical structure to the catalyst, including durability to withstand the ultra-high air flow, shock, and vibration environment typical of aircraft applications. The washcoat is a high surface area material applied to the substrate surface. It has a complex pore structure designed to optimize mass transfer of reacting gases to the active components on the washcoat surface. In aircraft applications, ozone decomposition is a first-order reaction, which means that chemical reaction rates are limited only by the amount of catalyzed surface area accessible to the reacting gases. Ozone conversion rates increase (decrease) with a corresponding increase (decrease) in accessible catalytic surface area. The active component, typical for aircraft ozone converter applications, is a platinum group metal that is well dispersed and fixed properly to the washcoat to assure high ozone decomposition performance and long operating life.

Each of the sub-components may be optimized to enhance catalyst functionality. For example, a more durable substrate material may be required for a converter designed to operate in a highly turbulent inlet gas flow. Similarly, a washcoat pore structure may be engineered to resist certain contaminants to a greater degree if their concentration in the converter inlet gas flow is expected to exceed typical design levels.

III. Ozone Converter – Catalyst Life Cycle

From a catalyst perspective, the ozone converter life cycle may be broken down into three distinct phases: fresh, returned, and restored. It is instructive to review certain aspects of each of these three phases and how performance data may be collected in each phase.

1. Fresh Catalyst

BASF is an OEM of both the converter and the catalyst it contains. When the converter leaves the factory, the catalyst it contains is in a “fresh” state, as illustrated in Figure 2.

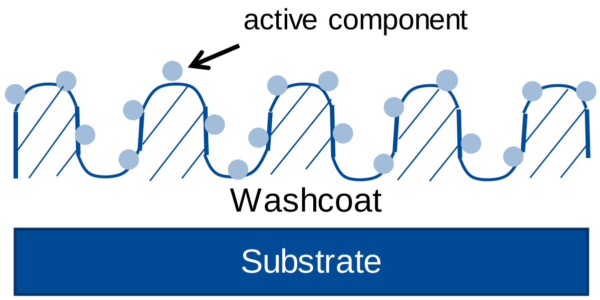

Figure 2. Schematic of fresh catalyst

The catalyst remains in its fresh state until it contacts a gas stream. A fresh catalyst has indefinite shelf life. That is, the catalyst does not lose activity solely due to the passage of time. The converter may be evaluated in this state to establish a fresh ozone (VOC) conversion performance, which may be used by analytics as a reference benchmark. In accordance with design requirements, each converter satisfies a minimum performance standard.

2. Returned ("As Received") Catalyst

BASF also provides MRO services on converters returned from the field. When the converter is received for servicing, its catalyst is in an "as received" state, as illustrated in Figure 3. The performance of the converter may be measured in this "as received" state prior to additional servicing.

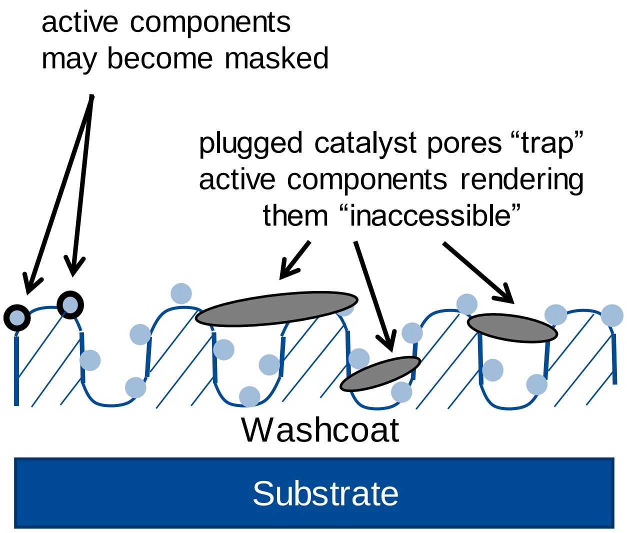

Figure 3. Schematic of catalyst in "as received" state

The catalyst "ages" by the progressive accumulation of surface contaminants that cover, or "mask", active components and/or washcoat pores, which renders the active components within these pores inaccessible to the reacting gases. The loss of access to these active components is perceived by test as a loss of performance relative to the fresh baseline reference. Although the catalyst has indefinite shelf life, it is standard practice to express the loss of catalyst activity as a function of aircraft flight hours. In this way, time, expressed as flight hours, is used as a surrogate for the contaminant accumulation rate to which the catalyst is exposed in the application.

In practice, the same catalyst may "age" differently in different applications as a function of the actual contaminants in the gas stream and their relative rate of accumulation. Typical contaminants of interest in aircraft ozone converter applications include sulfur, silica, and phosphorous. Typical sources of contaminants in the aircraft ozone converter application include ambient air and service vehicle exhaust during ground servicing of the aircraft, aircraft engine fluid leaks including lubricating oil, and leaks of various fluids into the bleed air stream including hydraulic fluid and de-icing fluids.

3. Restored Catalyst

As part of its MRO service, BASF has the capability to “wash” in-situ the catalyst within the converter housing and restore much of its catalytic activity. The “washed” state of the catalyst is illustrated in Figure 4. The ozone conversion performance of the “washed” converter may be measured before its return to service.

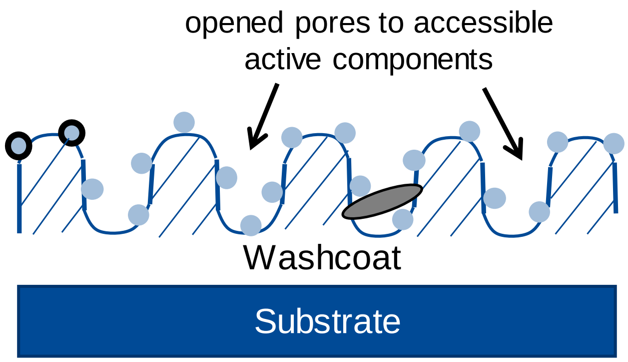

Figure 4. Schematic of catalyst restored by washing

The BASF MRO catalyst washing process effectively cleanses the pore structure of the washcoat and restores access to active components previously inaccessible due to pore plugging by contaminants accumulated during converter use. Although the washing procedure restores most of the catalyst activity, some contaminants may remain, being too deep within the pore structure to be removed, and thus have a slight, but measurable, impact on restored ozone conversion performance.

The BASF MRO service restores the catalyst to a near-fresh state and retains the durability of the initial catalyst structure – substrate, washcoat, and active component. No catalytic material is added to the structure; neither is the original catalytic material stripped off the surface and reapplied. These processes risk incompatibility with the original catalyst materials and may exhibit an accelerated catalyst aging rate upon return of the converter to surface if, for example, the additional active components are surface concentrated and thus too exposed to contaminants and/or particulate generation due to surface attrition of the added materials.

IV. BASF MRO Data Mining and Analytics

As both OEM and MRO service provider for the ozone and ozone/VOC converter, and catalyst technology developer, manufacturer, and MRO wash procedure originator, BASF is in a unique position to evaluate ozone and ozone/VOC converters through the catalyst life cycle – fresh, returned, and restored.

From this perspective, BASF conducted an analytics study of its MRO data to assess catalyst deactivation drivers and field deactivation trends. To constrain the complexity of the analysis by eliminating application specific design variables such as flow, temperature, etc..., the study focused only on ozone and ozone/VOC converters returned to BASF for MRO service over a three-year period after use on a certain long range commercial aircraft.

The MRO service data set included airline, converter serial number, flight hours (recorded as both "time since new" and "time since overhaul") and ozone conversion efficiency measured both "as received" and restored after the BASF MRO washing procedure. A nominal fresh performance value was incorporated as a comparative baseline reference. The data set was cut progressively into smaller subsets for each analysis:

1. General Population

   The General Population describes all ozone and ozone/VOC converters manufactured by BASF as OEM and returned to BASF MRO for service.

2. Initial Service Population

   The Initial Service Population describes those ozone and ozone/VOC converters manufactured by BASF as OEM and returned to BASF MRO for their initial service after first use.

3. Married Pairs

   Married Pairs describe those ozone and ozone/VOC converters from the Initial Service Population that operated on the same aircraft and were evaluated for ozone conversion performance by BASF MRO both before ("as received") and after service and washing.

Analytics focused on the following questions:

1. "How do ozone and ozone/VOC converters differentiate themselves in service, if they do, with respect to ozone conversion performance?"

2. "Can the differentiation, if it exists, be associated with catalyst deactivation drivers?"

3. "What are the implications of the analysis with respect to extending catalyst service life?"

V. General Population

Figure 5 presents a data cloud analysis of the ozone and ozone/VOC converters returned to BASF MRO for service over a three-year period after use on a certain long range commercial aircraft. The General Population extents are represented by the gray trapezoid. The Initial Service Population extents are represented by the subset green trapezoid. The reported “time since new” is recorded in flight hours on the x-axis. The ozone conversion measured for the converter in an “as received” state is recorded on the y-axis.

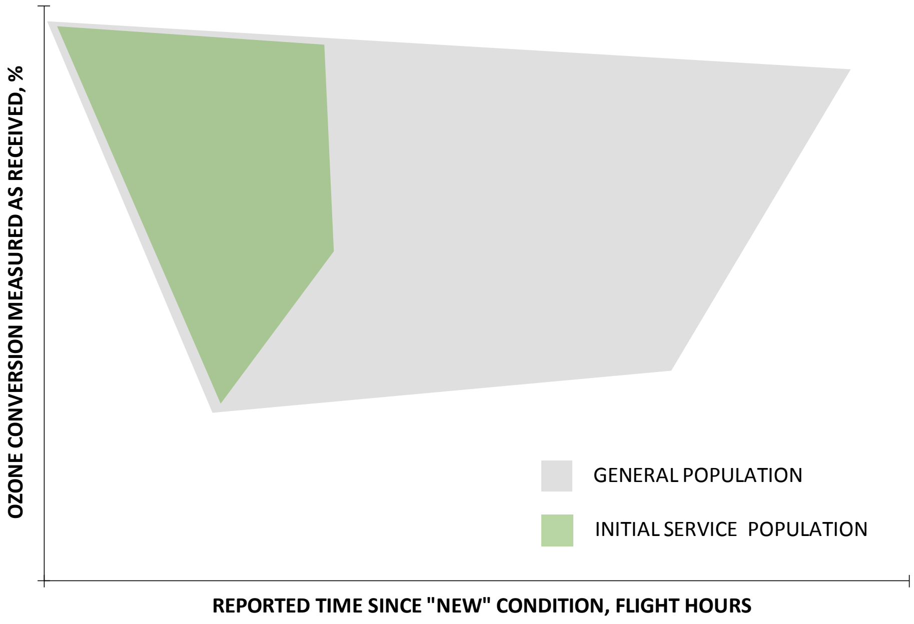

Figure 5. General Population of ozone and ozone/VOC converters

Several significant trends are evident in a comparison of the two populations. The breadth of the populations’ extents along the y-axis, in terms of ozone conversion measured in an “as received” state, highlights that catalyst “aging” – the progressive accumulation of contaminants – is influenced by many variables, some of which may be related to episodic, one-time events that are not well represented by time, flight hours, as a surrogate. The extents of the General Population along the x-axis, those converters serviced single or multiple times by BASF MRO, exceed the extents along the x-axis of the Initial Service Population, those converters receiving their initial service by BASF MRO after first use, by nearly a factor of three. The relative longevity of the general population testifies to the efficacy of the BASF MRO service in restoring catalyst activity while preserving the intrinsic durability of the catalyst architecture – substrate-washcoat-active component.

The cumulative service history of the converter is a significant variable in understanding its performance over time. If the converter is serviced in a manner consistent with its initial design, as is done by BASF MRO, then the “aging clock” is essentially “reset” when the catalyst is restored to a near-fresh condition. However, if the converter is serviced in a manner that changes the intrinsic design of the catalyst, such as by the addition, subtraction, or substitution of certain materials, then the “aging clock” is intrinsically disrupted and the time-aged history of the converter prior to such service is essentially destroyed.

Service history can be isolated as a variable in the analysis by considering only the Initial Service Population both before and after servicing by BASF MRO.

VI. Initial Service Population

Figure 6 presents a data cloud analysis of the Initial Service Populations of ozone and ozone/VOC converters returned to BASF MRO for service over a three-year period after use on a certain long range commercial aircraft. The Initial Service Population extents for the ozone converter population are represented by the blue trapezoid. The Initial Service Population extents for the ozone/VOC converter population are represented by the subset red trapezoid. The reported “time since new” condition is recorded in flight hours on the x-axis. The ozone conversion measured for the converter in an “as received” state is recorded on the y-axis. The scale of the axes is the same for both Figure 5 and Figure 6.

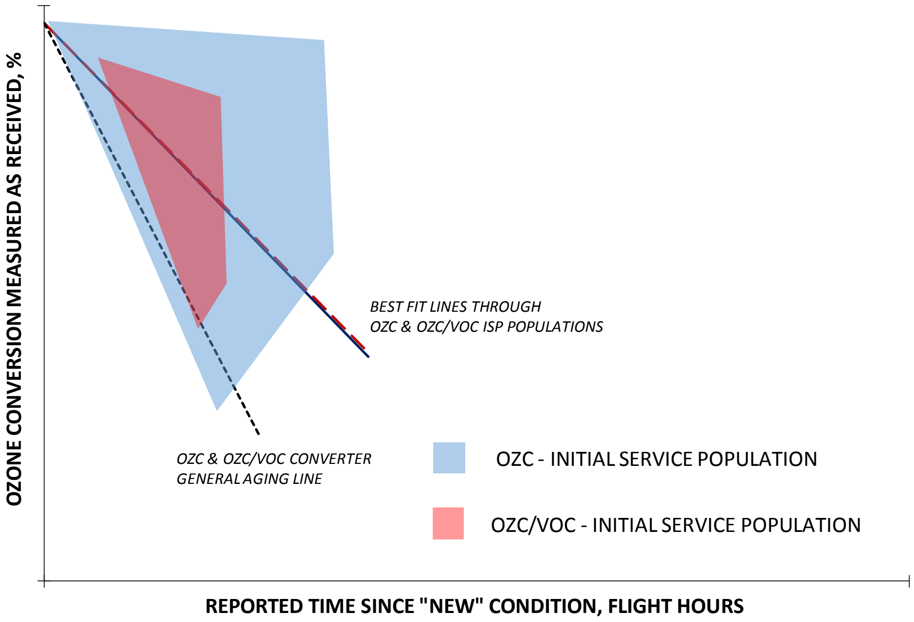

Figure 6. Initial Service Population of ozone converters and ozone/VOC converters

Although the extents of the ozone/VOC converter population appear to be slightly shifted towards fewer flight hours than the extents of the ozone converter population, a more insightful comparison of the two technologies can be made by comparing the best-fit lines through each of these populations. As shown in Figure 6, the best-fit lines are essentially collinear, which means that the ozone and ozone/VOC converters deactivate in a self-consistent manner. The introduction of VOC conversion functionality to the ozone decomposition catalyst does not disrupt the ozone conversion functionality or “aging” characteristics. Thus, ozone/VOC catalyst technology offers the benefit of VOC conversion without any drawbacks or trade-offs with respect to ozone conversion. The consistency of the technologies also allows cohort analysis of ozone conversion on subset populations of ozone/VOC converters to be extended to the larger population of ozone converters.

Episodic variability along the y-axis is seen in both ozone and ozone/VOC converter populations returned to BASF MRO for their initial service. One means by which to account for this variability in converter performance projections over time is to adopt a “General Aging Line”, which is drawn such that it bounds a fixed percentage of the field returned population. The "General Aging Line" thus sets a realistic definition of minimum expected performance for ozone and ozone/VOC converters in most operating environments in which those variables affecting progressive contaminant accumulation – aging – is either not well understood, not well monitored, or not well controlled.

VII. Married Pairs – OZC/VOC Converters

An ozone or ozone/VOC converter typically is installed on each bleed air stream from each aircraft engine on the aircraft. This suggests a natural cohort of converter "Married Pairs" – two converters from the same aircraft undergoing initial servicing by BASF MRO at the same time. Sequential converter serial numbers designated married pairs in the data set. The premise is that the Married Pair, installed on bleed air streams from "identical engines", share exposure to contaminant sources external to the aircraft and thus should be consistent in their "as received" ozone conversion performance.

Figure 7 presents a comparative analysis of the ozone conversion performance on Married Pairs of ozone/VOC converters for the same airline having a similar number of reported flight hours. The dark red column presents "as received" ozone conversion; the light red column presents the ozone conversion restored to the converter by BASF MRO service; the white column presents the nominal irretrievable loss of ozone conversion performance relative to a nominal, fresh value.

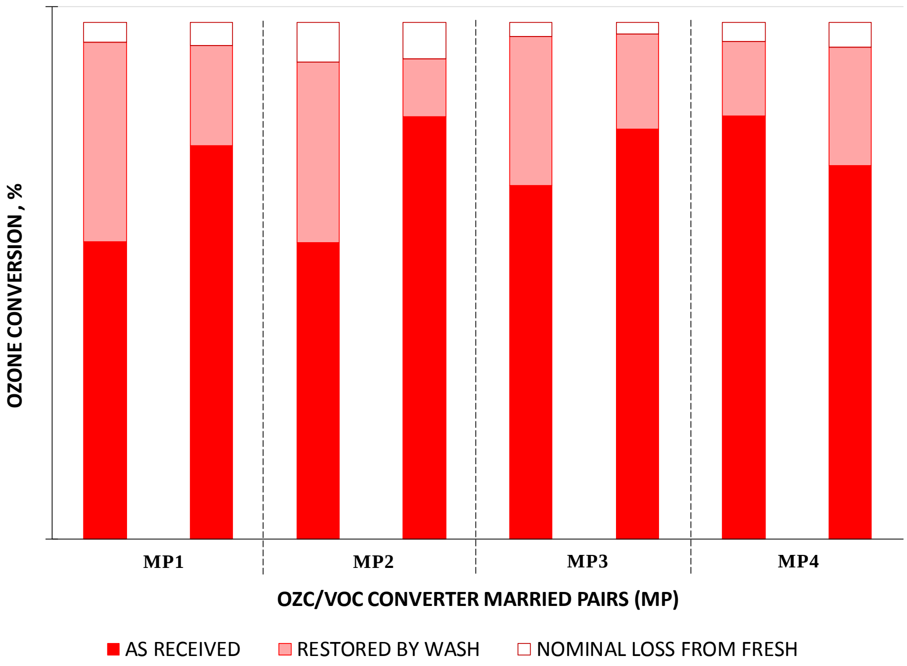

Figure 7. Married Pair population of ozone/VOC converters

The "as received" ozone conversion performance does not show good agreement within a Married Pair, as shown by the relative differences in the set of red columns. Each of the converters in the Married Pair have the same number of flight hours. The relative difference, then, may be associated with episodic contaminant events that by their nature are not well represented by flight hours as a surrogate. Localized leaks into the bleed air stream of one engine, for example, would differentiate the operating environment between the Married Pair with regards to contaminants.

BASF MRO service restores by wash significant ozone conversion performance, as represented by the light red columns, and consistency of total performance within the Married Pair, as represented by the dark red plus light red columns. The consistency across the Married Pair sets of the restored ozone conversion performance better reflects the consistency in the number of flight hours accrued prior to service by the converter set than would be suggested just by the "as received" performance.

A metric based on irrecoverable catalyst performance loss thus may track well with flight hours as a practical surrogate for catalyst aging.

VIII. Married Pairs – OZC Converters

1. Restored Ozone Converter Performance

The same analysis of "as received" versus restored ozone conversion performance can be applied to the larger cohort of ozone converter Married Pairs across multiple airlines within a similar range of accumulated operating hours. It is presumed that airlines may differ among themselves with regards to such variables as primary flight route(s), maintenance schedules, etc. that may contribute significantly to different progressive contaminant accumulation rates within the pore structure of the catalyst.

Figure 8 presents the restored ozone conversion performance averaged among all ozone converter Married Pairs for three airlines cohorts having similar average reported flight hours.

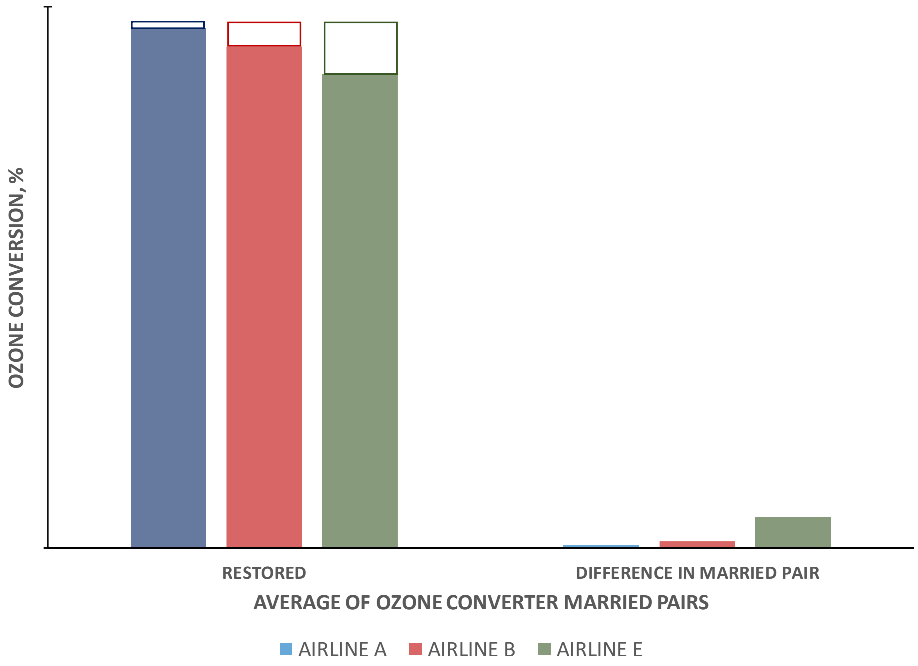

Figure 8. Married Pair population of restored ozone converters, average reported values

The airline cohorts differentiate themselves after BASF MRO service and wash in both average ozone conversion performance (left) and average difference in the Married Pair sets (right). Ozone conversion performance not able to be restored by wash is represented by the unfilled stacked white column for each airline. A metric based on irrecoverable catalyst activity loss may distinctively characterize the operating environment of the converter and thereby capture a measure of differentiation among airlines.

2. “As Received” Ozone Converter Performance

Figure 9 presents the “as received” average ozone conversion performance (left) and average difference in the Married Pair sets (right) for the same airlines of Figure 8.

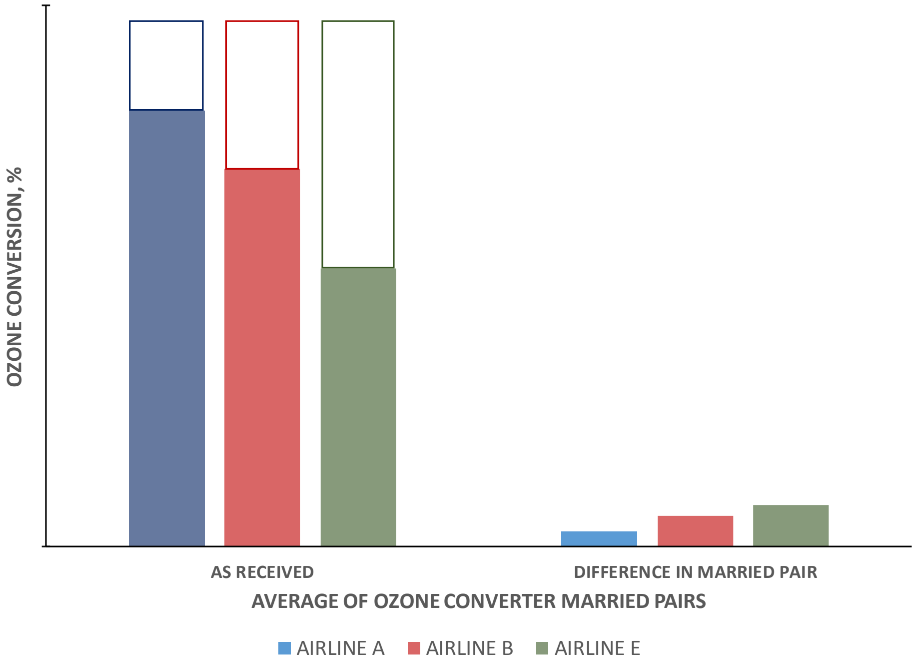

Figure 9. Married Pair population of “as received” ozone converters, average reported values

Ozone decomposition catalyst loses observed performance as its washcoat pore structure is progressively masked and plugged by the accumulation of catalyst contaminants. Although each ozone converter operating environment may be distinctively unique with respect to the specific contaminants accumulated and/or relative proportion of these contaminants, it is reasonable to surmise that a greater accumulation of masking contaminants causes not only a greater loss of access to active components, yielding a greater loss in observed ozone conversion performance, but also a greater probability of driving contaminants deeper into the washcoat pore structure whereupon they become irretrievably lodged yielding a permanent loss of performance. Thus, the relative ranking of airlines is preserved before (Figure 9) and after (Figure 8) service and cleaning. Likewise, a metric based on irrecoverable catalyst activity loss would preserve airline differentiation.

In summary, BASF’s data mining and analytics efforts applied to the BASF MRO service data have revealed an ozone conversion performance metric based on irrecoverable deactivation measured after a well-defined and robust BASF MRO service and wash procedure, itself intrinsically linked to deep knowledge of the catalyst architecture afforded by BASF OEM and catalyst manufacturing, that tracks well with reported flight hours as a surrogate for contaminant accumulation, differentiates among airlines as a surrogate for contaminant environments, and is mechanistically linked to general masking of catalytic surfaces, which directly affects observed ozone converter performance measured in the “as received” state after field use.

IX. Metric Analysis of the Initial Service Population

Having applied the metric successfully to the Married Pair cohorts of ozone and ozone/VOC converters, the population definition is now relaxed to that of the Initial Service Population, including both single and married pairs having any number of accumulated flight hours.

Figure 10 presents the metric ranking of airlines serviced by BASF MRO. The metric describes relative irrecoverable deactivation, or that portion of the catalyst performance that cannot be restored due to irrecoverable contamination. Since the metric describes the converter loss of performance, the relative ranking of airlines is an inverse of that presented in Figures 8 and 9.

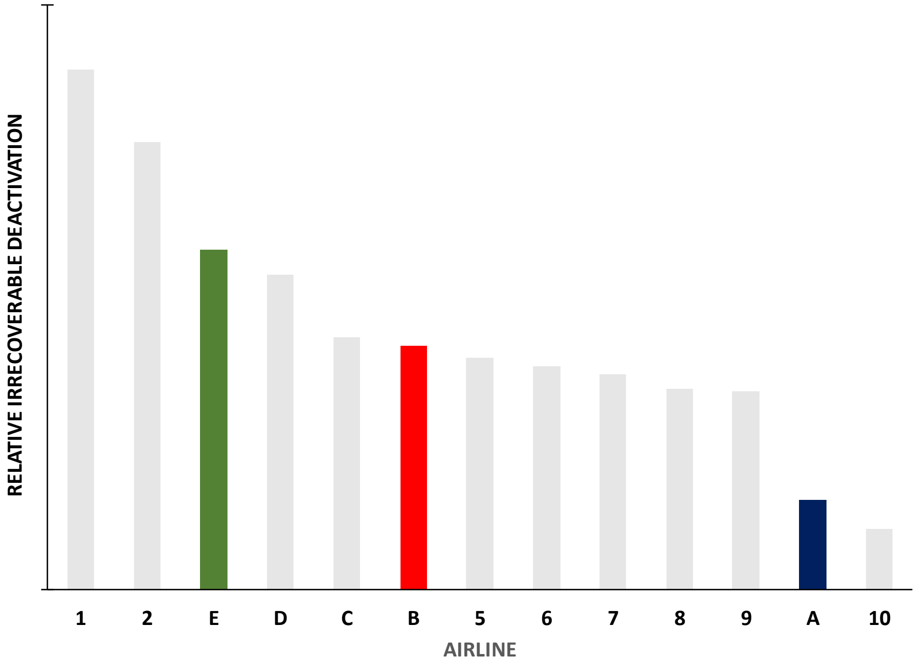

Figure 10. Metric ranking for Initial Service Population

Airlines A, B, and E are highlighted since their Married Pair populations were analyzed in the previous section. Expanding the analysis from just Married Pairs to the entire Initial Service Population unconstrained with respect to flight hours does not change the relative metric ranking of Airlines A, B, and E. This illustrates the general applicability of the metric in describing ozone converter field performance.

The Initial Service Population extents for Airline A, B, and E are presented in Figure 11. The global average, “as received” ozone conversion performance is presented as a data point for each airline in their respective shaded region. The “General Aging Line” is included for comparative reference and the axis scales are the same as in previous plots discussed in this white paper.

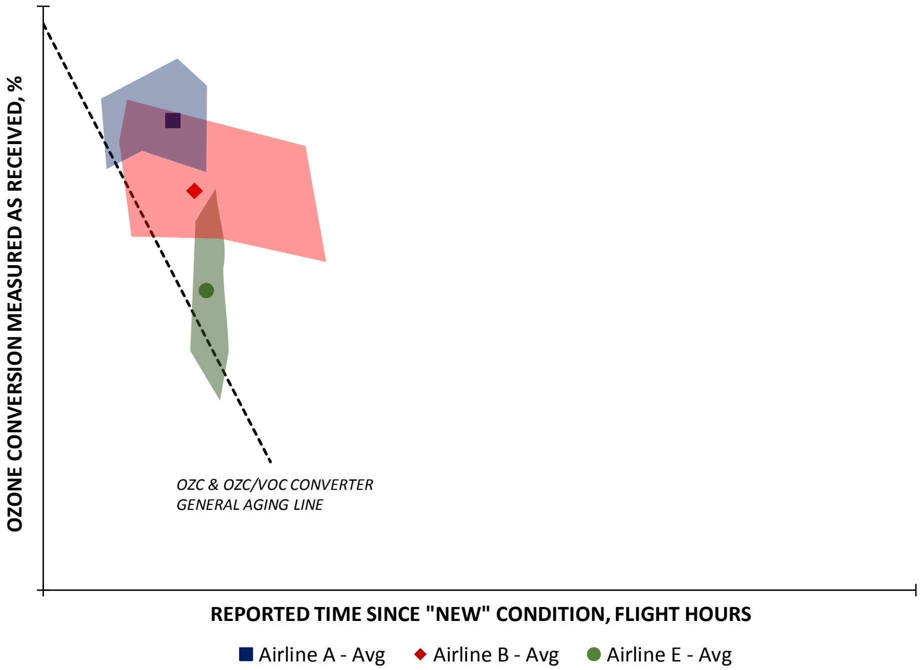

Figure 11. Initial Service Population extents comparison for certain airlines

The relative ranking of the airlines, emphasized by their global average data points, corresponds to the primary flight route characteristics of each airline: Airline A being oceanic, Airline B being land-based, Airline E being desert. Each flight route operating environment presents a different contaminant profile to the catalyst yielding a differentiation in ozone conversion performance.

The high degree of scatter for each region highlights the challenge that “as received” data poses to the crafting of a statistically significant model to predict or to constrain catalyst aging under field conditions and the need for additional metric development, such as reviewed in this white paper.

X. Summary

As a catalyst manufacturer and an ozone and ozone/VOC converter OEM and MRO service provider, BASF has the expertise, knowledge, and information to assess what drives catalyst performance in aircraft ozone abatement. BASF MRO service maximizes the restoration of catalyst activity while preserving the original, intrinsic durability of the catalyst design.

Analysis of the catalyst life cycle – fresh, returned, restored – reveals progressive contaminant accumulation that leads to irrecoverable washcoat pore blockage and masking as the prime means of catalyst deactivation. By quantifying the ozone conversion performance in each of the life cycle stages, BASF has developed a metric, which is based on irrecoverable catalyst activity loss, to assess ozone and ozone/VOC converter field performance. The metric shows self-consistency within a fixed airline data set of similar flight hours. The metric also differentiates ozone and ozone/VOC converter performance among airlines' data sets of similar flight hours and is consistent with relative trends in "as received" ozone conversion performance.

Establishing a converter product history with BASF offers the opportunity for an airline to differentiate their converter performance with respect to the "General Aging Line" for certain long range commercial aircraft. This differentiation, supported by BASF performance metric data analytics, may yield hidden value in optimization of converter service life and maintenance schedules.

About Us

BASF's Catalysts division is the world's leading supplier of environmental and process catalysts. The group offers exceptional expertise in the development of technologies that protect the air we breathe, produce the fuels that power our world and ensure efficient production of a wide variety of chemicals, plastics and other products, including advanced battery materials. By leveraging our industry-leading R&D platforms, passion for innovation, and deep knowledge of precious and base metals, BASF's Catalysts division develops unique, proprietary solutions that drive customer success.

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