Exhaust Toxicity Evaluation in a Gas Turbine Engine Fueled by Aviation Fuel Containing Synthesized Hydrocarbons

Bartosz Gawron[1], Tomasz Białecki[1], Anna Janicka[2], Maciej Zawiślak[2], Aleksander Górniak[2]
[1] Air Force Institute of Technology, Warsaw
[2] Wroclaw University of Science and Technology, Wroclaw
POLAND
bartosz.gawron@itwl.pl; tomasz.bialecki@itwl.pl; anna.janicka@pwr.edu.pl;
maciej.zawislak@pwr.edu.pl; aleksander.gorniak@pwr.edu.pl

ABSTRACT

Aviation is one of the fastest growing means of transport. Therefore, the emission of harmful products generated during aircraft turbine engine combustion processes is a significant problem. Indeed, the generated pollutants, such as gaseous pollutants, particulate matter, organic compounds, etc., have negatively affect the climate, air quality and human health.

Aircraft emissions differ with the engine type, the engine mode and used fuel. Engine emissions (with a thrust >26.7 kN) are measured according to a defined test, the landing and take off (LTO) cycle. Procedures for sampling, measurement, analysis and evaluation of gaseous emissions from aircraft engines are developed and described in SEA International - Aerospace Recommended Practices (ARP 1256 and 1533).

The problem of toxicity is increasingly being taken-up in various technical fields (e.g. automotive). In addition to defining the type of substance that induce negative effects, the way of its penetration into the body and the time of exposure to it is also important. In aviation-related literature, numerous publications in the field of testing the emission of exhaust gaseous components, particulates or volatile organic compounds can be found. However, there is a lack of research related to the evaluation of the real exhaust toxicity, e.g. how it affects living cells.

The aim of this study was to use a new exposure technique for testing the toxicity of turbine engine exhaust and to verify its suitability in this area. The paper presents an innovative BAT – CELL Bio – Ambient Cell method which consists of determining the real toxic impact of the exhaust gases on living cells. Herein, cytotoxicity was investigated using human A549 lung cells and mouse L929 cells.

Tests on full scale aircraft turbine engines are very complex and expensive. Therefore, a miniature turbojet engine was used for preliminary exploration. The research was also of comparative nature. The engine was powered by a conventional jet fuel and then by a conventional/synthesized hydrocarbon blend. Exhaust samples were collected in bottles by a special sampling method.

The test results show that the method used in this paper allows to determine turbine engine real exhaust toxicity during the combustion process. Furthermore, its application possibilities are not only limited to miniaturised engines, the Bat-Cell method can be used during full scale turbine engine tests. The next step, therefore, will be to conduct such tests. In addition, it appears that the data given in the aviation sector, mainly that related to the emission levels of several gaseous exhaust components (CO, NOx, CxHy) are insufficient. To fully describe the engine exhaust emissions, they should be supplemented with additional tests, i.e. in terms of toxicity.

1.0 INTRODUCTION

From the beginning of aviation, fossil hydrocarbon fuel was the source of power. However, recent research and development work conducted in the field of alternative fuels has led to the approval of synthetic components that can be blended up to 50% with conventional jet fuel, and used to propel turbine aircraft engines. The approving procedure for jet fuel candidates is described in ASTM D4054 [1] (1981).

In the literature on aviation, there are numerous publications [2-8] on the combustion products emitted from the gas turbine engine. Such works are on emissions research of the exhaust components, i.e., exhaust gases, particulate matter or volatile organic compounds. There is still, however, insufficient research connected with the evaluation of the actual toxicity of such combustion products.

It is generally known that hydrocarbon fuel is a toxic substance. Data on the toxicity of jet fuels were collected by Mattie and Sterner [9], yet, these papers were only studies of exposure of the respiratory tracks or of skin (in the form of water vapour, aerosol or liquid) of laboratory animals. Some other studies were, however, on the influence of aircraft fuel on certain cell lines [10,11]. The aim of these studies were to assess the effect of the exposure of Jurkat cells to contact with JP-8 fuel JP-8, and not with its combustion products.

The impact of the emitted exhaust gases on human health can be confirmed or excluded in studies of their actual toxicity. Moreover, evaluating the toxicity of mixtures is a difficult and poorly recognised research problem. With reference to the influence on human health, not only is knowledge of the quantitative composition of substances essential, but also is the proportions in which they exist in relation to each other. The occurrence in the mixture of a few substances with known toxicological characteristics can result in additive synergism, or conversely, in eliminating the negative impact of some components on human health [12].

The most commonly used measurements are coefficients of equivalent toxicity based on indirect or direct experimental studies (through legal standards, e.g. allowable concentrations) [13-20]. This measure, however, is relative and depends both on the compound adopted as a reference mark and on the frequently changing legal regulations. It can also be based on different, sometimes conflicting, experiment results. It should not be forgotten that toxicity of a substance mixture to this extent is defined as a sum of coefficients calculated for a single compound. Thus, this method does not involve the potential interaction between individual compounds in the mixture (increasing, cumulating or abolishing its mutual toxicity) [21].

To obtain a fuller and more actual picture of the toxic effect of the exhaust gases on the human organism, barring the coefficients of equivalent toxicity, it is reasonable to study the cell cytotoxicity of gases affecting the human organism. The only currently available research tool in this area is a patented, innovative BAT-CELL method, established in cooperation with the Technical University in Wroclaw and the Polish Academy of Sciences. Here, a special device is used for the test, and tests are conducted on lines of cuticle cells of human lung tissues, since human respiratory tracks of a human are that which are most exposed to contact with compounds present in the exhaust gases [22].

The article presents the use of the innovative BAT – CELL Bio – Ambient Cell method in determining the actual toxic impact of the exhaust gases on living cells. The studies were carried out via a test rig with a miniature turbojet engine powered with conventional turbine aviation fuel and its blend with synthesised hydrocarbons from Hydroprocessed Esters and Fatty Acid (HEFA) process. The usefulness of the Bat-Cell method to test the toxicity of exhaust gases from the turbine engine was previously demonstrated in preliminary testing [23].

2.0 EXPERIMENTAL SETUP

2.1 Description of exhaust gases toxicity evaluation

The tests were performed in collaboration with the Institute of Immunology and Experimental Therapy – Polish Academy of Sciences in Wroclaw. The tests were done in triplicate, for each research date, for all test and control samples. Herein, the repeatability of obtained results was 95%, which indicated a level of difference in the number of cells in each of three experiments of only a few counted cells.

Tests were performed on two cell-lines to obtain an image of the impact of exhaust gases on the human respiratory tract and skin (the tissues most exposed to gas). These cell-lines are:

- L929 – a line of fibroblast-like cells obtained from the subcutaneous adipose tissue of a mouse C3H (ATCC CCL 1);
- A549 – a line of cuticle-like cells of the human lung (ATCC CCL 185).

All cell cultures were maintained in Eagle's culture fluid, supplemented with 10% inactivated (30 min, 56°C) calf serum and 100 U/ml penicillin, 100 µg/ml streptomycin and 2mM/ml L-glutamine, at temperature 37°C, in an atmosphere of 5% CO_2. The cells were grafted using a 0.05% solution of trypsin with 0.02% EDTA in PBS, with pH 7.2.

In a specially optimised sample, a combined cell culture of L929 and A459 at a density of $1x10^6$ cells/ml was created and incubated for 24 hours at temperature 37°C and an atmosphere of 5% CO_2. After this time, the cell fluid was removed, and a single-layer cell culture was transported to the laboratory of the Faculty of the Vehicle Engineering at the Technical University in Wroclaw. Here, tests were carried out utilizing a dedicated test rig, through the application of the BAT-CELL method.

Figure 1 presents a diagram of the device used to measure the toxic impact of exhaust gases on living cells.

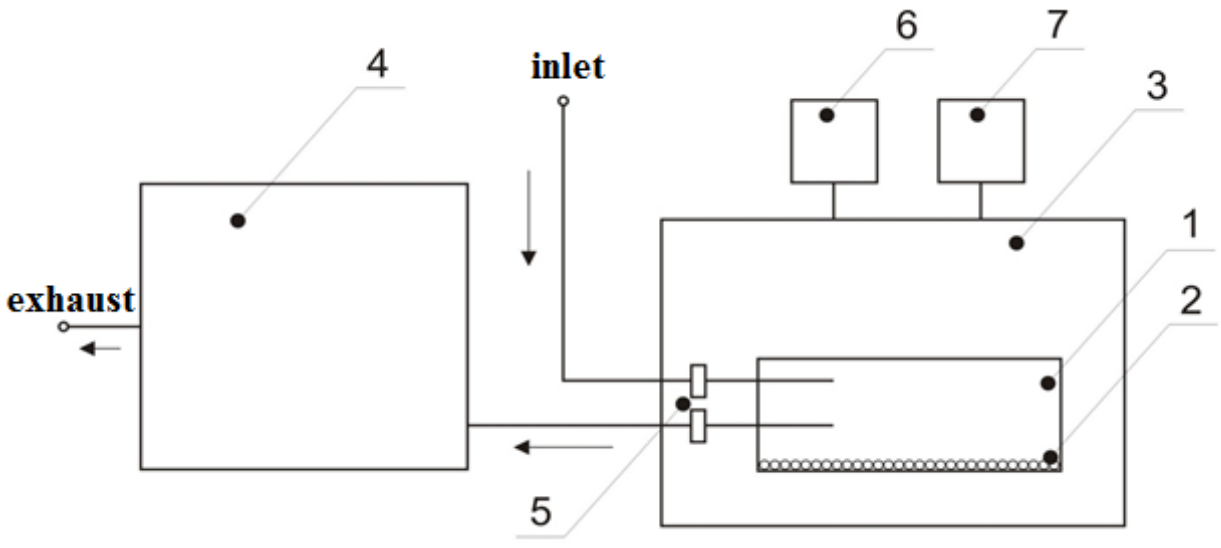

Figure 1: Diagram of the device to evaluate the toxicity of exhaust gases according to the original methodology of BAT-CELL Bio-Ambient-Tests, where: (1) sampler (sterile chamber), (2) cell line devoid of culture fluid (3), conditioning chamber equipped with pressure sensor, (4) aspiration system, (5) antibacterial filter, (6) and (7) temperature sensor

Gas samples were collected by way of a special aspirator in Tedlar bags with a capacity of 10 dm3. These were then connected to the BAT-CELL device. Quantitative and morphological changes in these cells when

under the influence of the examined exhaust gases were evaluated after 48 hours, using an inverted microscope.

2.2 Test rig

Figure 2 shows the test rig. This consists of three elements:

- miniature jet engine GTM-140 (generating combustion products);
- probe analyser (pipe and bags);
- device used to evaluate the toxicity of exhaust gases – Bat-Cell.

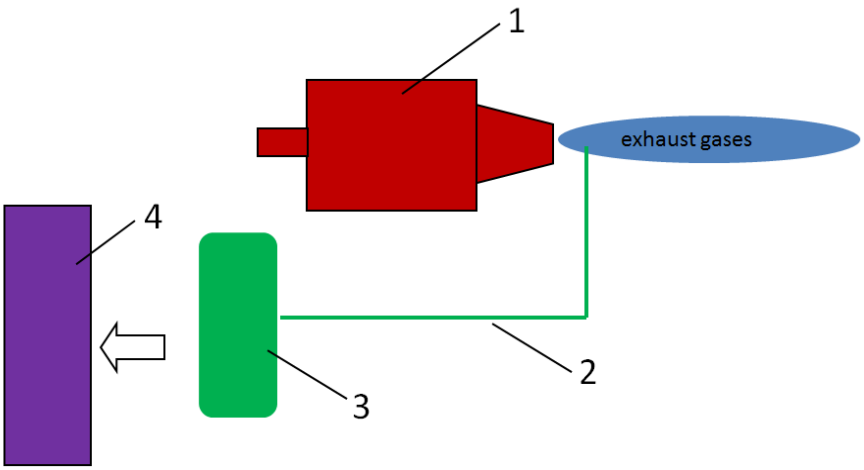

Figure 2: Test rig to estimate the toxicity of exhaust gases: 1 – miniature jet engine, 2 – pipe removing exhaust gases, 3 – bags for the collection of exhaust gases, 4 – Bat-Cell device.

Basic technical data were compiled in Table 1. The engine is the main component of a MiniJETRig, constructed in the Air Force Institute of Technology (ITWL). It is used in development and research works, mainly in tests of alternative fuels for aviation [3-5,22], in other non-aeronautical applications [25], and in other related projects [6,23,24].

The structure and research possibilities of the test rig were presented in [26], but precise data concerning the sensors used in establishing engine parameters and the emission of exhaust gases were described in [27]. During toxicity studies, the following parameters were measured: engine thrust, rotational speed, exhaust gas temperature and fuel consumption.

Table 1: Turbine engine specifications.

Engine Type	Turbojet – Single spool
Series Engine	GTM 140
Compressor	Single stage radial compressor
Combustion chamber	Annular combustion chamber
Turbine	Single stage axial flow turbine

Pressure ratio	2.8:1
Minimum RPM	33 000
Maximum RPM	120 000
Thrust at max. RPM	140 N
Fuel consumption at max. RPM	500 ml/min
Mass flow at max. RPM	0.35 kg/s
Max. Exhaust Gas Temperature	1023 K

Samples used to assess toxicity were collected using a special aspiration system (Figure 3), and then the gases were forced into the BAT-CELL device to provoke the exposure of cells to their effect.

a) b) c)

Figure 3: a) Tubes for the collection of exhaust gases, b) tube with the installed bag for exhaust gases, c) bags filled with exhaust gases.

The device (Figure 4) used to measure the influence of the actual exhaust gases on living cells according to the BAT-CELL method has sterile closed chambers located in the conditioning chamber situated within the rectangular housing. In the conditioning chamber, there is an antibacterial filter. The conditioning chamber is also provided with pressure and temperature sensors. The whole device is additionally equipped with an aspiration system (aspiration panel). The aspiration system is connected with the sterile closed chamber through an inlet pipe supplying exhaust gases to the sterile closed chamber. This then leads to the outlet pipe for removing the post-tested sampled exhaust gases.

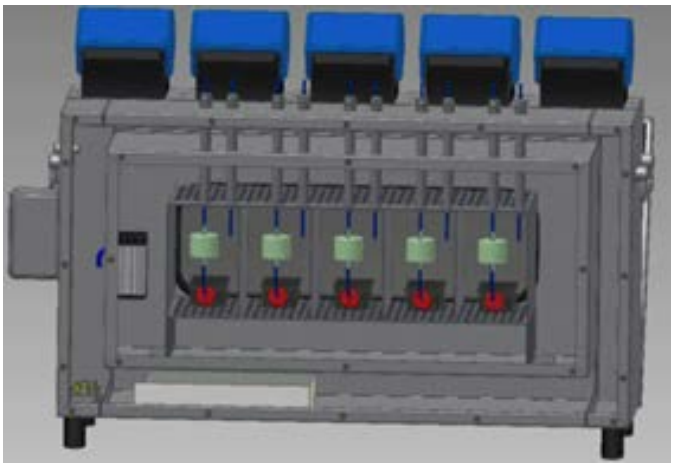

Figure 4: Device to measure the impact of the actual exhaust gases on living cells according to the BAT-CELL method.

2.3 Procedure

The engine test procedure for both examined fuels was the same (Figure 5). After starting the engine with a given fuel and reaching idling speed (approx. 33 000 rpm), the rotational speed was gradually increased to a determined value, i.e. approx. 80 000 rpm. This speed corresponds to the average load and operation of the GTM 140 engine. It ensures the possibility of taking realistic toxicity measurements in standard operating ranges. The test was run long enough to collect the exhaust gases into Tedlar bags.

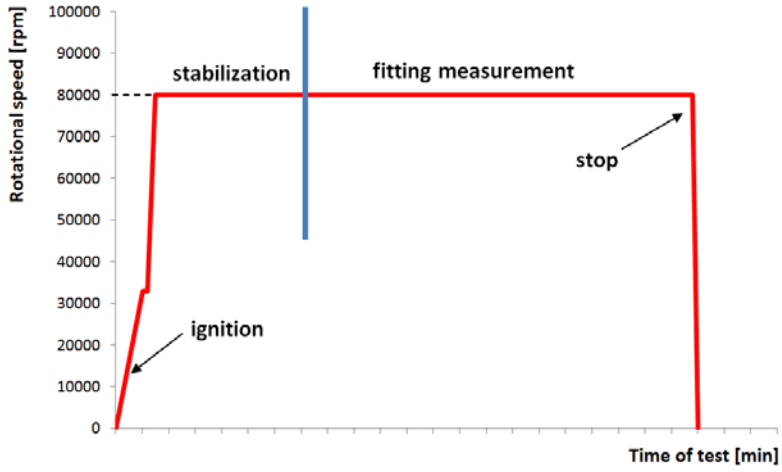

Figure 5: Profile of engine test during toxicity tests of exhaust gases.

After reaching the rotational speed of approx. 80 000 rpm, 2 minutes were set aside to stabilise the thermodynamic state of the engine and thus the combustion process (‘stabilisation’ in Fig. 5). This sampling delay was set, because, while all engine parameters at all ranges stabilise quite fast, after previous experiences [27], it has been recognized that the emission of exhaust gases - mainly CO, is characterised by significant value changes in the initial periods of operation at the given range. Hence, after 2 minutes, actual sampling test was conducted (“fitting measurement” in Fig. 5). This consisted in collecting exhaust gases in the appropriately prepared Tedlar bags and then forcing the accumulated gases into the BAT-CELL device.

2.4 Tested fuels

The tests involved the use of a neat kerosene-type jet fuel (Jet A-1) and its blend with a synthesized hydrocarbons from HEFA process. The blend, containing 48% synthetic component – Camelina feedstock, is defined as 'HEFA/CAM'.

The above mentioned HEFA is currently one of five processes approved by the American standard ASTM D7566 [28] as technology for generating a synthetic component for aviation turbine fuel.

Table 2 shows the selected physicochemical properties of the examined fuel. Based on the results, the synthetic component (HEFA/CAM) is distinguished by having a considerably higher viscosity and, concurrently, a higher calorific value.

Table 2: Selected properties of tested fuels.

Lp.	Property	Unit	Method	Requirements	Test results	
					Jet A-1	HEFA/ CAM
1.	Density in 15 ºC	kg/m^3	ASTM D 4052	od 775 do 840	788.0	779.9
2.	Viscosity in -20 ºC	mm^2/s	ASTM D 445	max 8.0	2.992	5.004
3.	Heat of combustion	MJ/kg	PN-C-04062	min 42.8	43.45	43.70
4.	Smoke point	mm	ASTM D 1322	min 18	25	31
5.	Aromatics	% (V/V)	ASTM D 1319	max 25	15.8	9.4
6.	Naphthalenes	% (V/V)	ASTM D 1840	max 3.0	0.40	0.56
7.	Lubricity	mm	ASTM D 5001	max 0.85	0.83	0.77
8.	Flash point	ºC	ASTM D 56	min 38	43.5	44.5
9.	Surface tension	mN/m	PN-90/C-04809	-	24.89	25.06

3.0 RESULTS AND DISCUSSION

Table 3 presents the cumulative results in the range of measured engine operating parameters for both tested fuels. For every parameter, the average value and standard deviation were defined. Of note, the standard deviation was not determined for fuel consumption expressed in [g/s], because this parameter is calculated via the measurement of fuel consumption in [ml/min], as well as the determination of fuel density.

Table 3: Results of engine operating parameters.

	JETA-1		HEFA/CAM		Relative difference HEFA/CAM and JETA-1 [%]
	Average value	Standard deviation	Average value	Standard deviation	
Rotational speed [rpm]	80 910	± 815	80 988	± 524	+ 0.1
Thrust [N]	60.0	± 0.3	60.2	± 0.3	+ 0.3
Temperature behind turbine	495	± 5	494	± 5	- 0.1
Fuel consumption [ml/min]	186.3	± 2.4	171.4	± 1.9	- 8.0
Fuel consumption [g/s]	2.45	-	2.23	-	- 8.9

Based on the obtained results, it can be seen that for both tested fuels, the measurements were characterised by measured parameter high stability and repeatability (minute standard deviation values). For both fuels, for the same rotational speed (difference 0.1%), the engine generated the same thrust (a difference of 0.3%), and the behind temperature of the turbine was identical (a difference of 0.1%). Notable changes, not resulting from measurement error (the minute standard deviation values), of the examined fuels, were observed in measurements of fuel consumption (a difference of 8%). After taking into account the density of fuels, the difference in fuel consumption expressed in [g/s] reached 8.9%. The HEFA/CAM was distinguished by lower values of fuel consumption in comparison to those of Jet A-1, which is confirmed in the obtained values of selected physicochemical properties.

In evaluating toxicity whether the type of fuel, the number of cells not damaged due to the exhaust gases was determined. Figure 6 shows the amount of the lung (line A549) and skin cells (L929) per millilitre. The higher the number of morphologically correct cells, the less toxic were the gases to which cell lines were exposed.

Both with reference to a cell line and a skin line, it can be concluded that the number of damaged cells is significantly less in relation to exhaust gases from HEFA/CAM combustion than from conventional fuel. Based on test results, it can be stated that the additive of a synthetic component to Jet A-1 has considerable influence on the reduction of the toxicity of exhaust gases. With regard to the A549 cell lines, the toxic effect is strongly correlated with the exposure time. The longer the exposure time, the stronger the toxic effect. Still, the results are not unequivocal with respect to the subcutaneous tissue cell line (L929).

The results of tests confirm the legitimacy of the applied method of exhaust gas toxicity evaluation during the jet engine combustion process. It should be noted that the tests were preliminary and will be developed in the future from the methodological and statistical perspective.

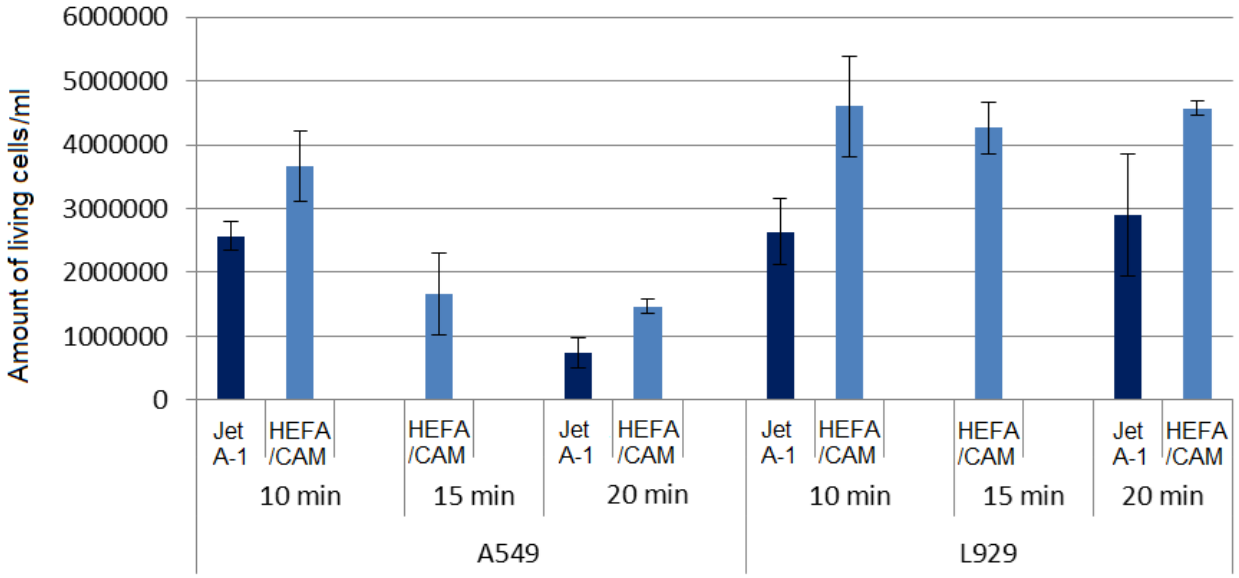

Figure 6: Results of toxicological tests expressed in the amount of living cells per ml in the function of exposure time.

4.0 CONCLUSION

Through the application of an innovative method, the BAT-CELL Bio Ambient Test process, the actual exhaust gas toxicity emitted by the miniature turbine jet engine was defined. The tests were conducted on two fuel types: Jet A-1 fuel and its blend with HEFA component. Both tested fuels are approved for use in turbine aircraft engines.

Engine tests results indicate that HEFA/CAM was characterised by lower fuel consumption values in comparison to neat Jet A-1. The other parameters of engine operation were comparable for both fuels. The additive of a synthetic component to conventional jet fuel, however, brought about a significant reduction in exhaust gas toxicity. Exhaust gases from HEFA/CAM combustion are considerably less toxic than that in the case of conventional jet fuel. This conclusion was confirmed for both tested cell lines (human lung cell line (A459) and mouse skin cell line (L929).

The tests presented in this article are innovative with reference to examining the actual toxicity of aircraft turbine engine exhaust gases. The tests, carried out on a miniature jet engine, also confirm the usefulness of the applied Bat-Cell method, not only in assessing the toxicity of current aviation turbine fuels, but also in the search for new, more environmental-friendly fuels. The BAT-CELL method can also be utilised for tests performed on full-scale turbine engines. The only caveat is that the engine exhaust gases are properly collected and supplied to the measuring device.

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