IMPACT OF PRE-COMBUSTION TREATMENT TECHNOLOGIES BY FUMIGATION (P-CTTF) ON INTERNAL COMBUSTION ENGINE (ICE) DECARBONIZATION EFFICIENCY AND POLLUTANT EMISSION REDUCTION

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Abstract: *Despite the accelerating trend toward vehicle electrification through hybridization, internal combustion engines remain essential contributors to global mobility. Their continued use highlights the need for efficient decarbonization and pollution reduction strategies. In this context, Pre-Combustion Treatment Technologies by Fumigation (P-CTTF) represent an emerging solution characterized by structural simplicity, low cost, and high functional impact. By introducing simple yet highly effective substances through the intake system, P-CTTF enhances combustion quality, reduces emissions, and contributes to cleaner and more reliable ICE operation. Up to now, most studies addressing fumigation-based pre-combustion treatments have been conducted on laboratory engines operating under controlled conditions and generally in good mechanical state, without significant wear or functional issues. As a result, the reported benefits mainly reflect idealized scenarios rather than real-world engine behaviour. In the work presented here, the focus shifts toward practical applicability by examining the effects of combined intake fumigation using potassium permanganate and ammonium nitrate on two high-mileage Diesel engines installed in production vehicles and exhibiting clear technical problems. This approach provides a more representative assessment of P-CTTF performance under realistic operating conditions, where carbon accumulation, component degradation, and irregular combustion are already present. The results obtained demonstrate how such simple, low-cost fumigation treatments can influence decarbonization efficiency, emissions behaviour, and overall engine response in vehicles that deviate substantially from laboratory-grade conditions.*

Keywords: *P-CTTF, decarbonization, pollution reduction, fumigation, Diesel engines*

1. INTRODUCTION

In light of recent geopolitical developments and the persistent uncertainty surrounding the large-scale feasibility of fully electrified propulsion systems, the automotive industry has undergone a significant shift toward hybrid vehicle technologies. This transition has resulted in an unprecedented expansion of hybrid powertrain adoption across multiple market segments. Nevertheless, despite their enhanced architectural complexity, hybrid systems remain fundamentally dependent on the internal combustion engine, which continues to exhibit well-known limitations, particularly in terms of environmental impact and pollutant emissions.

From a historical perspective, the progressive increase in internal combustion engine (ICE) complexity, driven primarily by the pursuit of higher efficiency, has occurred through two major developmental leaps.

The first was triggered by the oil crises of the 1970s and focused on reducing fuel consumption, alongside the widespread adoption of Diesel engines. The second, initially gradual during the 1990s and intensifying markedly throughout the 2000s in response to global warming concerns, had the primary objective of mitigating pollutant emissions. This latter phase led to the near disappearance of several inherently efficient engine concepts—characterized by low specific mass and volume—such as two-stroke engines and the rotary (Wankel) engine, as well as to the progressive encumbrance of Diesel engines with increasingly complex aftertreatment and emission control systems.

It should be noted that, in many instances, measures originally implemented over time with the primary objective of enhancing engine performance have also indirectly contributed to reductions in pollutant emissions, as exemplified by the following developments: the use of advanced materials (e.g., metallic alloys, ceramic-based materials and composite systems) exhibiting favorable thermophysical properties, thereby contributing to improved energy balance, increasing the operating pressures within the combustion chamber, improvements in the properties of fuels, lubricants, and cooling systems, the optimization of gas exchange processes, the increase of operating engine speeds and compression ratios, the optimization of combustion chamber architecture, the electronic control of engine processes and other auxiliary engine subsystems. In some cases, it is difficult to clearly delineate between auxiliary systems introduced primarily for emission reduction and those intended exclusively for performance enhancement, as these objectives are often closely interrelated and pursued simultaneously, as exemplified by technologies such as water injection.

On the other hand, the growing urgency to reduce pollutant emissions has also led to the introduction of additional auxiliary systems specifically dedicated to this objective. Figure 1 illustrates several examples of such auxiliary installations that have been incorporated into internal combustion engines primarily to address emission mitigation requirements.

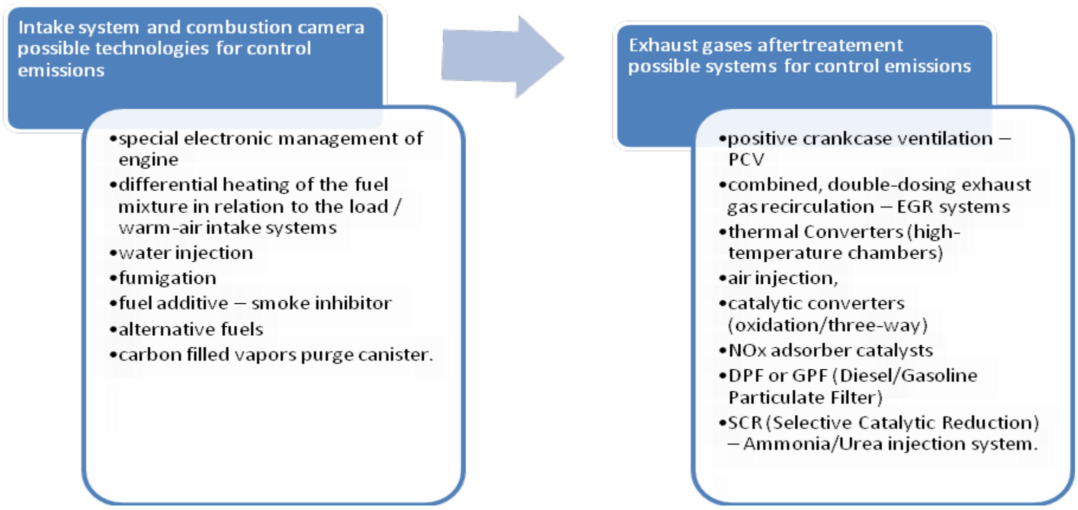


FIG. 1 Some exclusive methods added to ICE in order to decrease the pollution

As can be readily observed, the complexity of internal combustion engines has reached a very high level. Such increased complexity has the potential to affect overall system reliability, especially given the rapid proliferation of electronic components and sophisticated control architectures involved in modern engine operation.

What actions can be taken in this context? A plausible approach involves reducing the number of system components and simplifying their overall architecture. One viable method to achieve this objective is the enhancement of the effectiveness of existing emission-reduction strategies, with particular emphasis on those solutions that are economically viable and already widely implemented.

Pre-combustion treatment technologies by fumigation (P-CTTF) may represent a viable response to the aforementioned challenges, as they constitute a cost-effective yet efficient approach for both reducing pollutant compounds in exhaust gases and promoting the internal cleaning/decarbonizing of the engine by mitigating carbonaceous deposit formation, which is a natural consequence of normal engine operation.

2. STATE OF THE ART – INTERNALLY DEVELOPED P-CTTF TEST CASES

The research concept—significant portions of which have been presented in [1–5]—that ultimately led to the approach first designated in [5] as *Pre-Combustion Treatment Technologies by Fumigation (P-CTTF)* originated from the application of chemistry as a fundamental science within the fuel–oxidizer–internal combustion engine system, as well as from the analysis of the chemical reactions initiated during the combustion processes occurring inside the ICE.

Each of the conducted tests yielded conclusions that proved relevant for guiding and refining subsequent research directions.

Accordingly, with respect to the implementation of fumigation using electrolysis-derived gases (HHO/Brown gas) [1–2], the investigations highlighted the non-negligible role of nitrogen—otherwise considered an inert gas—through its potential involvement in energetic phenomena when saline water (NaCl solution) was introduced into the system [2]. These observations were reported even in the apparent absence of a direct ignition source, underscoring the need for a more detailed analysis of the underlying physicochemical interactions.

As a synthesized conclusion derived from the experimental investigations conducted using fumigation with electrolysis-generated gases, the following observations can be stated:

1. In both investigated configurations, a common drawback was identified in the requirement for an additional auxiliary installation of non-negligible complexity, namely an electrolytic cell, which entails continuous electrical energy consumption. This additional energy demand may adversely affect the overall efficiency of the system, with the potential for the global energy balance to become negative.
2. In the majority of practical scenarios, on-board hydrogen production achieved through an independent electrolytic cell is unable to deliver a positive net energy balance. This limitation arises from the well-known low energetic - and even economic - efficiency of hydrogen produced via electrolysis, as reported in the literature [7].

Although the experimental investigations formally reported in [1] and [2] did not achieve full success, the conclusions derived from these studies provided sufficient motivation to continue the experimental program based on the same fundamental principle, namely intake manifold fumigation with various substances serving as working fluids, not necessarily fuels. The primary objective of this approach is to promote in-cylinder combustion processes whose outcomes may result in a measurable reduction of pollutant emissions, potentially enabling the elimination of several costly auxiliary systems dedicated exclusively to emission control, as illustrated in FIG. 1.

To this end, and driven primarily by considerations of economic efficiency, the use of expensive, complex, and bulky electrolytic cells was abandoned. Instead, the experimental focus shifted toward simple, non-electronically controlled atomizers. These devices are intended to be evaluated both on simplified laboratory engines, operating without additional aftertreatment systems, and on established production engines equipped with conventional emission control technologies.

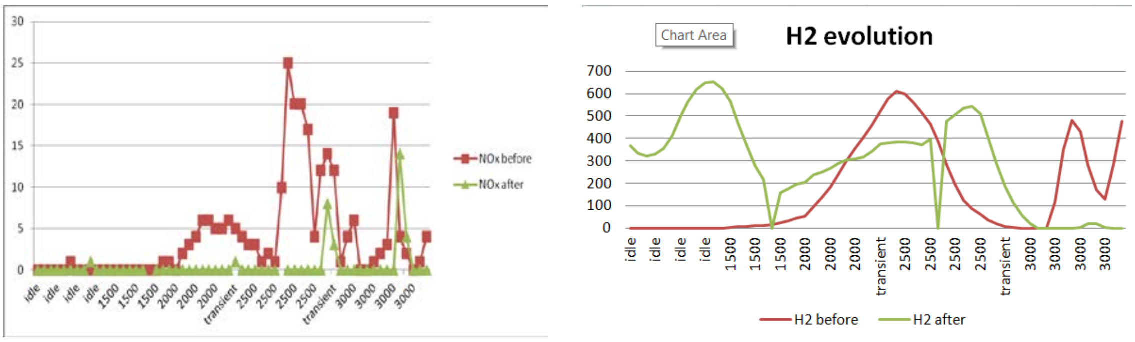
Chronologically, the first extensions of the investigations reported in [1–2] were conducted under laboratory conditions using a single-cylinder Diesel engine operating in a controlled environment. The results of these experimental studies were presented and discussed in detail in [5].

The results obtained from tests conducted on three common, mass-produced vehicles appeared to be considerably more interesting. These vehicles had accumulated high mileage, and one of them also exhibited engine malfunction error codes.

For all three vehicles, exhaust emissions were measured under an operating regime corresponding to a predefined decarbonization cycle. This procedure constituted the primary objective of the test, particularly for the vehicle that exhibited engine error codes and irregular fluctuations in engine speed.

Accordingly, the first vehicle subjected to testing was a passenger motor vehicle, specifically a *Dacia Sandero* with a 1,390 cm^3 engine displacement and an accumulated mileage of 109,603 km. For the fumigation process, two atomizers, each with a flow rate of 30 mL/h, were employed, using a solution consisting of 250 mL of pH-neutral water and 25 g of ammonium nitrate/NH_4NO_3 (corresponding to a 10% cold-solution mixture). The detailed results were reported in [3]. In addition, and as a synthesis complementing the findings presented in [3], the following additional observations were recorded:

- CO_x emissions exhibited a significant reduction;
- moreover, despite the increase in exhaust gas temperature, NO_x emissions also decreased (FIG. 2(a) - result not published in [3])
- during the test, a significant amount of water was observed to be discharged through the exhaust pipe (a possible explanation being an increase in H_2 emissions - see FIG. 2(b), result not published in [3] - which reacted immediately with O_2, thereby forming water);
- throughout the test, a persistent characteristic odor, similar to that associated with fireworks, was detected;
- during the test, maintaining a constant engine speed proved difficult, as it exhibited persistent fluctuations that were hard to control;
- shortly after the completion of the test and the publication of the corresponding data in [3], major malfunctions of the tested engine were reported, manifested by irregular engine operation and the illumination of the "*Check Engine*" warning light on the dashboard. Diagnostic analysis revealed clogging of the catalytic converter, which necessitated repeated forced regeneration procedures until the issue was resolved (the engine returned to normal operation, the warning indicator was extinguished, and the diagnostic error code was cleared). This outcome further demonstrates and highlights that the applied treatment effectively cleaned the internal components of the engine. However, the downside of this process was that coarse particles forcibly detached from the combustion chamber led to clogging of the catalytic converter - a problem that was resolved only with difficulty through multiple subsequent forced regeneration cycles.



(a) (b)

FIG. 2 Evolution of NO_x (a) and H_2 (b) during the tests performed on the passenger motor vehicle (MAS), as detailed in [3]

3. TESTS CONDUCTED ON MASS-PRODUCED DIESEL ENGINES USING P-CTTF TECHNOLOGY - METHODOLOGY

The identification data and the main technical characteristics of the tested vehicles, as well as other general information related to the experimental researches, are presented in Table 1:

Table 1. Main data related to the conducted tests

	Test 3.1	**Test 3.2**
Vehicle	*Opel Astra Sports Tourer*	*Ford Focus Tournier*
Date of manufacture	27.06.2011	06.11.2007
Mileage (km)	125.414	186.667
Engine	1686 cm^3 CDTI/Diesel fuel	1560 cm^3 TDCi/Diesel fuel
Engine power	81 kW = 110 CP	80 kW = 108,8 CP
Emission standard	EURO 5	EURO 4
Malfunctions	Irregular engine operation and difficulties during acceleration; fault code: P0409 (EGR position sensor performance, intermittent); possible EGR valve clogging	No visible malfunctions; normal engine operation
Purpose of the procedure	1. cleaning of the EGR system through the application of a decarbonization cycle; 2. elimination of malfunctions and clearing of the fault code; 3. reduction of opacity.	1. cleaning of the EGR system through the application of a decarbonization cycle; 2. reduction of opacity.
Emission analyser	OPA-100 opacimeter (*BrainBee Automotive*)	
Parameter monitoring tool	Bosch KTS-560 tester (including monitoring of the start and end times of DPF/Diesel Particulate Filter regeneration events)	
Tools used for implementing the specific P-CTTF procedure	Simultaneous use of two atomizers (each capable of 30 mL/h flow rate), operating at constant flow and without electronic control: 1. 250 ml of water with pH neutral + 25 gr. ammonium nitrate (NH_4NO_3) = 10% NH_4NO_3 cold solution mixture; 2. commercial pharmaceutical - grade potassium permanganate solution ($KMnO_4$) – 0,02% $KMnO_4$ solution.	

The air filters of the two engines subjected to testing were removed, and the two atomizers were installed in their place, as illustrated in FIG. 3.

(a) (b)

FIG. 3 Removal of the air filters and installation of the two atomizers for the Opel (a) and Ford (b) engines, respectively

For both engines, a cleaning procedure cycle was applied, which was defined based on preliminary unofficial tests conducted on a relatively small number of engines and subsequently underwent repeated modifications following the observations recorded throughout multiple test campaigns. Consequently, an evolution of the phases of this cycle was established, including variations observed between the three official tests—the first of which had its results published in [3], and the latter two being reported in the present paper—as shown in Table 2.

Table 2. Decarbonization/cleaning Cycles/procedures Employed

	Tests					
	Cleaning cycle used in [3]		**Cleaning cycle used in Test 3.1**		**Cleaning cycle used in Test 3.1**	
Preliminary phases	Engine warm-up to the working conditions/nominal operating temperature					
	Measurement of exhaust emissions **before** cleaning procedure		Measurement of opacity **before** cleaning procedure			
	Duration [minutes]	**Engine speed [rpm]**	**Duration [minutes]**	**Engine speed [rpm]**	**Duration [minutes]**	**Engine speed [rpm]**
1st phase	5	aprox. 750-800 (idle operating regime)	3	aprox. 750-800 (idle operating regime)	5	aprox. 750-800 (idle operating regime)
2nd phase	10	2000	10	1700-2550	20	2000
3rd phase	10	2500	3 violent accelerations to 3800 rpm		5	gentle accelerations till 3000 rpm
4th phase	5	gentle acceleration 2000→3500	2	aprox. 750-800 (idle operating regime)	5	2000
5th phase	5	2000	-	-	5	aprox. 750-800 (idle operating regime)
6th phase	5	gentle acceleration 2000→3500	-	-	-	-
7th phase	3	aprox. 750-800 (idle operating regime)	-	-	-	-
Final phase	Measurement of exhaust emissions **after** cleaning procedure		Measurement of opacity **after** cleaning procedure			

4. TESTS CONDUCTED ON MASS-PRODUCED DIESEL ENGINES USING P-CTTF TECHNOLOGY - RESULTS

The results obtained in Test 3.1 are presented in Table 3.

Table 3. Results obtained from the test conducted on the *Opel Astra Sports Tourer*

Stage	Opacity	DPF regeneration
Before cleaning procedure	**K = 0,07 [m-1]** **K = 3,0 [%]**	Inactive (last regeneration: 93 km ago) Soot concentration DPF: 26% Coolant temperature: 98^0C
After cleaning procedure	**K = 0,90 [m-1]** **K = 32,2 [%]**	Inactive (last regeneration: 93 km ago) Soot concentration DPF: 26% Coolant temperature: 99^0C

Observations: the applied treatment effectively cleaned the internal components of the engine; however, the quantity of soot released was sufficiently large that the engine continued to operate abnormally, with opacity increasing by more than one order of magnitude (from 3.0% to 32.2%). As can be observed, the coolant temperature remained consistently higher than normal (98–99 °C), indicating that the engine was not operating under nominal conditions. The DPF did not detect a sufficient upstream/downstream pressure differential to trigger a regeneration event. It is likely that the elevated exhaust gas temperature resulted in the combustion of particulate matter into sizes that were not retained by the DPF. The procedure was forcibly terminated after a significant temperature increase upstream of the DPF was observed on the diagnostic tester, which could have led to degradation of the particulate filter.

It was decided to repeat the test under more careful and comprehensive monitoring of parameters specific to the internal processes, using an engine without technical issues. This led to the implementation of Test 3.2.

A selection of the relevant results obtained in this test (3.2) is presented in Table 4 (the experience gained during Test 3.1 enabled the monitoring and annotation of a larger set of relevant parameters, which are highlighted in bold in the table). The final results obtained exclusively for opacity are shown in Table 5. Notably, zero opacity was achieved at the end of the procedure.

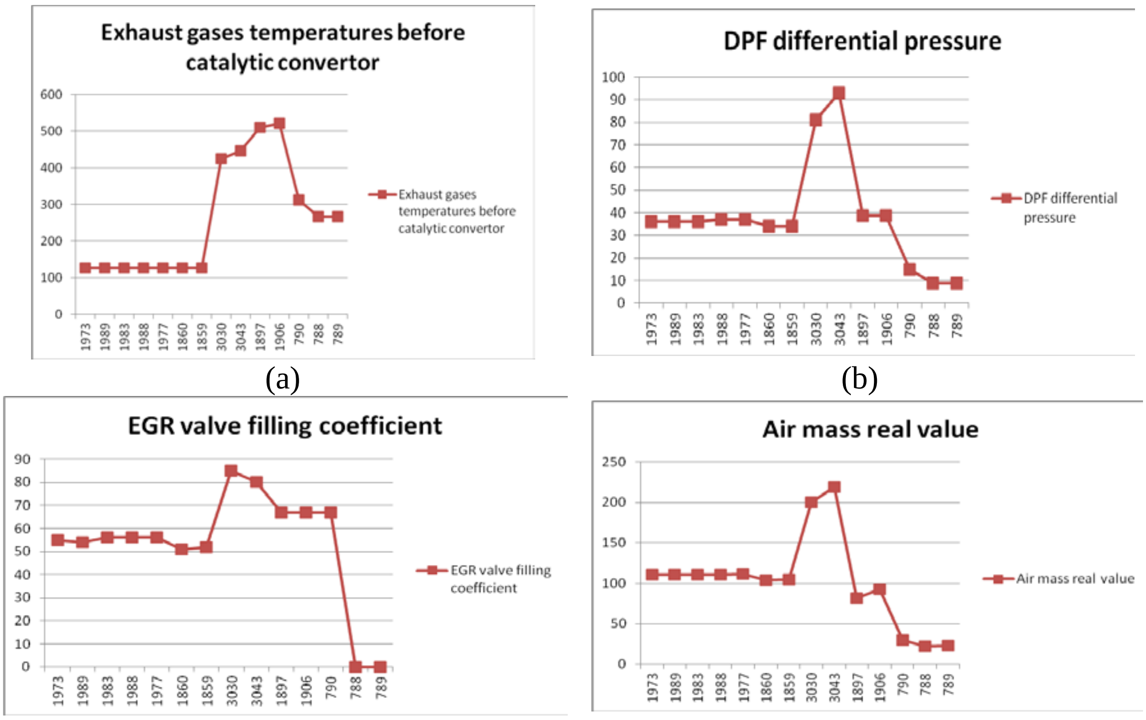
Table 4. Selection of data obtained during the monitoring of Test 3.2

Stage	Engine speed [rpm]	Coolant temperature [^{0}C]	Exhaust gas temperature upstream of the catalytic converter [^{0}C]	DPF differential pressure [mbar]	EGR valve filling coefficient [%]	Mass air flow – actual value [kg/h]
2nd phase	1973	79	126	36	55	111,1
2nd phase	1989	79	127	36	54	111,0
2nd phase	1983	79	127	36	56	111,2
2nd phase	1977	79	126	37	56	111,8
2nd phase	1860	79	127	34	51	104,3
2nd phase	1859	79	127	34	52	105,1
3rd phase	3030	80	**425**	**81**	**85**	**200**
3rd phase	3043	80	**447**	**93**	**80**	**219,3**
4th phase	1897	79	**509**	39	67	82,2
4th phase	1906	79	**521**	39	67	93,3
5th phase	790	78	312	15	67	29,7
5th phase	788	78	267	9	0	22,4
5th phase	789	78	266	9	0	22,6

Table 5. Results obtained from the test conducted on the Ford Focus Tournier

Stage	Opacity	DPF regeneration
Before cleaning procedure	**K = 0,04 [m-1]** **K = 1,6 [%]**	Inactive (last regeneration: 62 km ago)
After cleaning procedure	**K = 0,00 [m-1]** **K = 0,0 [%]**	Inactive (last regeneration: 62 km ago)

In accordance with the data presented in Table 4, an evolution of the monitored parameters as a function of engine speed was obtained, as illustrated in the charts shown in FIG. 4.



(a) (b)

(c) (d)

FIG. 4 Evolution of the main monitored parameters as a function of engine speed

Observations during the test:

– During the opacity test, no visible smoke was emitted during acceleration and, consequently, the measured opacity at the end of the test was zero both at idle and during acceleration.
– During deceleration, some smoke was observed and the opacimeter registered opacity values of K = 0.12–0.14; however, these values were not recorded due to the short response time of the instrument.
– At the end of the test, the exhaust pipe exhibited an odor apparently similar to ammonia; a comparable distinctive odor was also noted during the test reported in [3]. (A common element in both tests is ammonium nitrate; however, in Test 3.2 potassium permanganate was also involved.)
– Despite the zero opacity measured at the end of the test, just before engine shutdown, slight smoke emissions were still observed during a few acceleration events, although these were not captured by the opacimeter.

CONCLUSIONS

1. The tests confirm that the applied procedure (P-CTTF in the ammonium nitrate + potassium permanganate configuration) effectively cleans the internal components of the engine.
2. For engines with extensive internal deposits, there is a risk of a relatively violent release of solid particles resulting from the elevated internal temperatures induced by the applied procedure. This phenomenon may lead to damage to the catalytic converter and/or the DPF due to excessive clogging, or even to structural degradation caused by particulate impact on the internal substrate.
3. The temperatures upstream of the catalytic converter exhibit relatively abrupt increases, which, in extreme cases, may lead to actual thermal damage of the catalyst or even pose a fire hazard.
4. There is a risk of sudden DPF loading with particulate matter, for which it is not guaranteed that removal can always be achieved either through the elevated temperatures generated by the applied procedure or through standard - or even forced - DPF regeneration processes.

Final conclusion: Considering the positive outcome obtained - namely, zero opacity at the end of the procedure (see Table 5) - the question arises as to the possible elimination of the DPF, particularly in cases where intake water injection is available and can be combined with fumigation using a mixed ammonium nitrate + potassium permanganate solution, precisely as specified by the P-CTTF technology. Nevertheless, the decarbonization cycle employed, as well as its application frequency, must be carefully optimized and properly controlled in order to mitigate and eliminate the risks outlined above.

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