

Development of a Super-Light Substrate for LEV III/Tier3 Emission Regulation

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Abstract

With the increasing number of automobiles, the worldwide problem of air pollution is becoming more serious. The necessity of reducing tail-pipe emissions is as high as ever, and in countries all over the world the regulations are becoming stricter.

The emissions at times such as after engine cold start, when the three-way catalyst (TWC) has not warmed up, accounts for the majority of the emissions of these pollutants from vehicles. This is caused by the characteristic of the TWC that if a specific temperature is not exceeded, TWC cannot purify the emissions. In other words, if the catalyst could be warmed up at an early stage after engine start, this would provide a major contribution to reducing the emissions. Therefore, this research is focused on the substrate weight and investigated carrying out major weight reduction by making the porosity of the substrate larger than that of conventional products. A lightweight substrate achieving about 31% weight reduction compared to conventional technology, and a conventional substrate with the same cell structure were both mounted into vehicles and a comparison performed. The results showed that, for the lightweight substrate, the time taken for light-off at which it purified the emissions was reduced compared to conventional products.

Introduction

U.S. tail-pipe emissions regulations are becoming increasingly stringent year after year. LEV III /Tier3 regulation requires average fleet NMOG+NOx emissions to 30mg/mile by 2025 as illustrated in [Figure 1](#).

In order to reduce tail-pipe emissions, it is necessary to increase the performance of TWC. However, responding by simply increasing the amount of precious metals (PGM) coated on the catalysts would present an issue from the perspective of cost. [Figure 2](#) shows that the majority of HC emissions occur during the cold start. Emission of HC is discharged in several seconds after cold start [1]. This result shows that emission gas purification using TWC is difficult on low-

temperature conditions like after cold start. Then, development of substrate which reaches light-off more quickly of the catalyst at an early stage is important. This work will investigate substrate properties that promote earlier TWC light-off. This paper will discuss the basic properties of the developed substrate and the verification of catalyst performance in an actual vehicle.

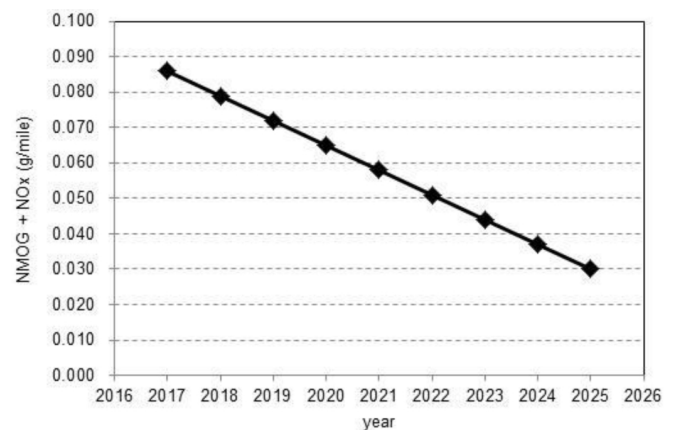


Figure 1. LEV III /Tier3 NMOG+NOx fleet average regulation.

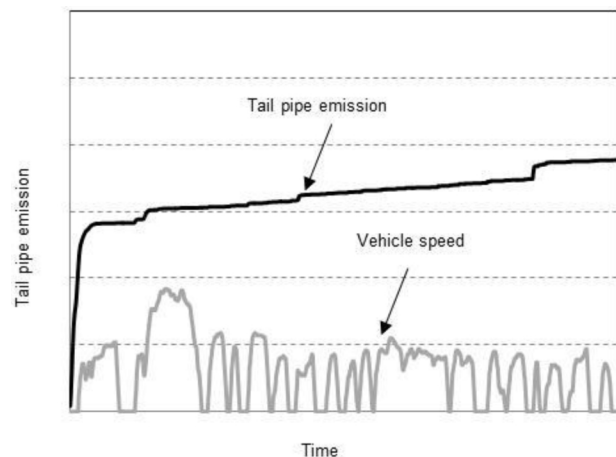


Figure 2. An example of tail-pipe HC emission.

Concept of High-Porosity Substrate

A number of methods of realizing early TWC light-off can be considered, but the main approaches are increasing the temperature of the exhaust gas or reducing the weight of the catalyst or the substrate. However, increasing the temperature of the exhaust gas generally has a negative effect on the thermal efficiency of the engine, reducing fuel efficiency [2]. Moreover, the rising in exhaust gas temperature also has the problem of heat deterioration of an exhaust manifold etc. On the other hand, it is known that the reducing the weight of a catalyst has an effect in early light-off. In order to reduce the weight of the catalyst, it is necessary to reduce the quantity of the washcoat. The washcoat material produces a surface area due to its high pore volume, increasing contact between the exhaust gas and the precious metals in the catalyst. Its reduction could lead to declines in performance. Reduction of the washcoat also results in sintering of the precious metals [3]. To help avoid these issues, the present research focused on the reduction of the weight of the substrate as a method of realizing early TWC light-off. However, reduction of the weight of the substrate can also potentially result in a variety of issues. In order to reduce the weight of the substrate without changing the cell structure, it is generally necessary to reduce the density of the material. This reduces the weight of the substrate, but also necessarily results in issues including loss of strength and reduction of resistance to thermal shock [4][5].

This work investigated properties and effect of new developed light weight substrate. The weight of the substrate has been reduced by increasing the porosity of the material in comparison to a conventional substrate. The high porosity is paths to improve product performance. There have been advances in pore forming and microstructural design. Porosity of 55% is attained at current substrate wall thicknesses (2 and 3 mil) while meeting a suite of requirements including strength and compatibility with three way catalyst washcoat. The technology brings a significant improvement in light-off performance to reduce vehicular emissions while ensuring that other performance targets are still satisfied. Wall thicknesses below 2 mil are required for standard porosity materials to reach the same thermal mass as offered by developed substrate. Technology to make substrates wall thickness below 2 mil is not ready today.

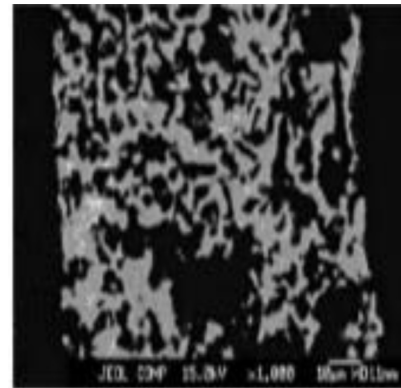
A Physical Property

Evaluation Samples

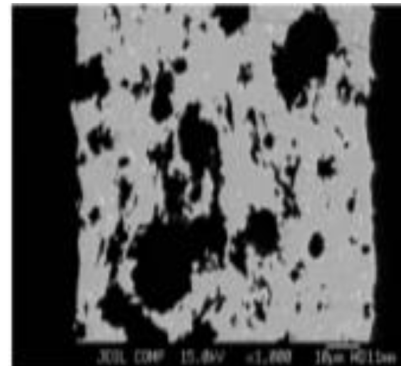
A new high porosity substrate was developed using a new material system and process optimization for scale up. Table 1 shows properties of the developed substrate including cell structure and ratio by weight. The realization of a 20% increase in porosity against a conventional substrate has reduced weight by 31%. It was considered that this would contribute to early warm-up of the catalyst. Figure 3 shows SEM images of cross sections of the developed substrate and a conventional substrate. These images show the substrates in their bare states, not coated with catalyst layers. The images clearly indicate that the porosity of the walls of the developed substrate is greater than that of the walls of the conventional substrate. The performance of the developed substrate was compared with that of the conventional substrate in a variety of areas.

Table 1. Comparison of properties of substrate

	Developed substrate	Conventional substrate
Cell density (cspi)	600	600
Wall thickness (mil)	3	3
Porosity (%)	55	35
Ratio by Weight	0.69	1.0



(a)



(b)

Figure 3. SEM images of (a) developed substrate and (b) conventional substrate

Back Pressure

The back pressure of the developed substrate was measured in order to verify that its cell structure was the same as that of the conventional substrate and that it would have no effect on engine output or fuel efficiency. Measurements of pressure drop were conducted using a system making it possible to accurately control the flow of clean and dry air up to a flow rate of 360 Nm³/h at room temperature.

Figure 4 compares pressure drop for the developed substrate and a conventional substrate. The substrates were compared in a bare state, without a catalyst coating. The results verify that there is no difference in pressure drop between the developed substrate and a conventional substrate.

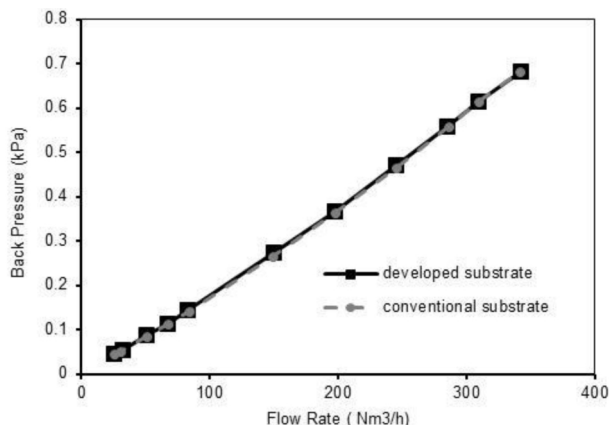


Figure 4. The Back pressure of (a) developed substrate and (b) conventional substrate

Thermal Durability

In order to verify the thermal durability of the developed substrate, a test were applied to fresh substrate and substrates subjected to two types of thermal oven aging. Table 2 shows the aging conditions.

Table 2. Two kinds of aging condition

Aging 1	950°C 150Hours
Aging2	750°C 30min × 3

Isostatic strength was measured in order to study changes in the strength of the three types of substrate under the conditions shown in Table 2. The results are shown in Figure. 5. It was verified that isostatic strength is not reduced by aging. The results can be considered to indicate that the developed substrate is sufficiently strong to be durable in actual use.

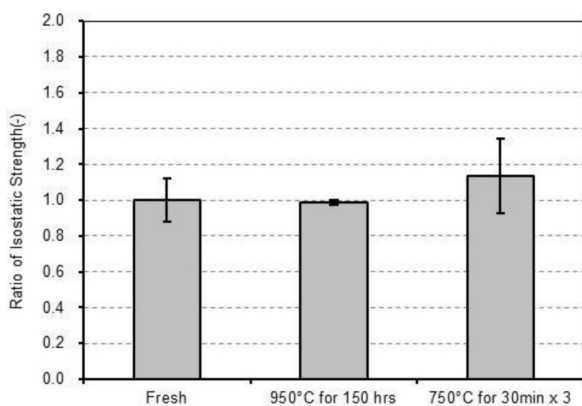


Figure 5. The isostatic strength of Fresh substrate and aged substrates

Vehicle Test Conditions

Catalyst Coating and Aging

The developed substrate was coated with a catalyst in order to verify its effect in an actual vehicle. Washcoat amount is 275g/L, and the same method of coating was employed as is used for conventional substrates. The coated precious metals were palladium and rhodium in this study. The catalysts were aged using gasoline powered engine

with 4-cylinder 2.4L. The catalysts were aged at an average temperature of 950°C for 50 hours, and the engine was operated using a combination of stoichiometric, rich, and lean air-fuel ratios.

Vehicle Description

The catalysts were equipped in an actual vehicle to verify their performance. The engine was a 4-cylinder 2.4 L model using a close-coupled and an under-floor catalyst. The under-floor catalyst used a conventional substrate, and the close-coupled catalyst used either the developed substrate or a conventional substrate, for the purposes of comparison.

Temperature was measured at the points shown in Figure 6. Exhaust gas temperature was measured for the close-coupled and the under-floor catalyst, and each catalyst temperatures at 40mm into the bed were measured. Tail-pipe emission and temperature comparisons were conducted in FTP mode based on U.S Emission test procedure.

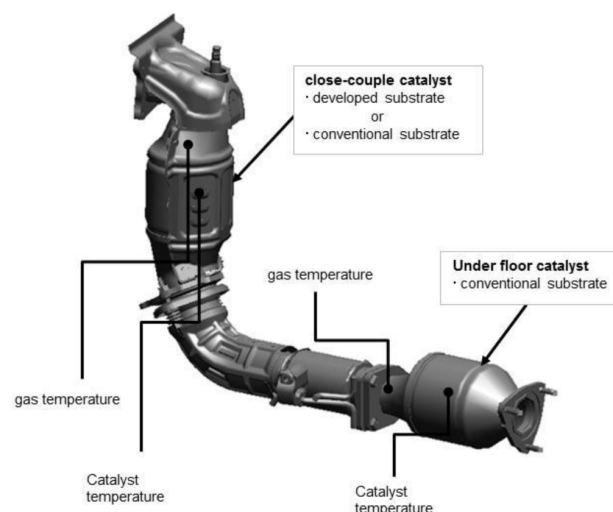


Figure 6. Schematic image of catalyst layout and measuring point of temperature.

Results and Discussion

Figure 7 shows a comparison of the temperature of the close-coupled catalysts from engine start to 100 sec in FTP mode. The results indicate a difference in temperature between the catalysts after engine start. At the point of vehicle start, the temperature difference between the developed and the conventional substrates was 77°C.

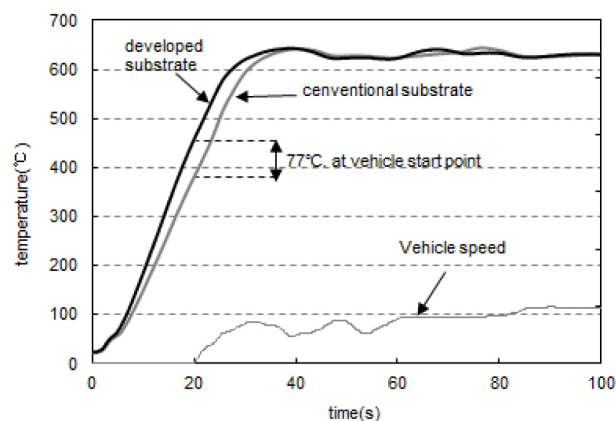


Figure 7. A comparison of the temperature of the close-coupled catalysts from engine start to 100 sec in FTP mode.

Figure 8 shows a comparison of the temperature of the under-floor catalysts. The temperatures of the under-floor catalysts were compared when the close-coupled catalyst used the developed substrate, and when it used the conventional substrate. Because the temperature of the exhaust gas flowing to the under-floor catalyst was higher in the case of the close-coupled catalyst using the developed substrate than the catalyst using the conventional substrate, the increase in the temperature of the under-floor catalyst was more rapid.

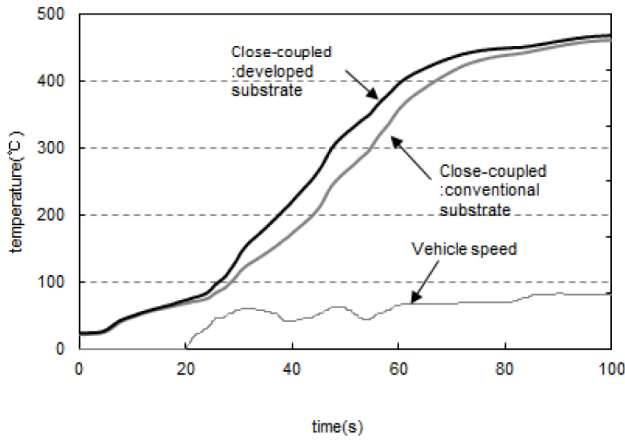


Figure 8. A comparison of the temperature of the under floor catalysts from engine start to 100 sec in FTP mode.

Figure 9 shows the tail-pipe emissions on the same time scale of figure 7 and 8. The results show that the catalyst using the developed substrate starts purification of THC emission earlier than the other catalyst, and this is considered to be an effect of earlier catalyst light-off due to earlier temperature rising.

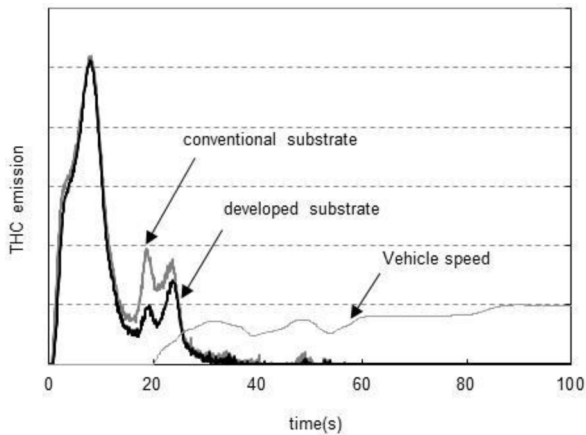


Figure 9. A comparison of THC emission.

Figure 10 shows temperature profiles from 100 to 500 sec after engine start. The transitions in temperature are largely identical, but points at which there are significant declines in the temperature of the catalyst using the developed substrate can be observed. These are points at which fuel to the engine is cut as the vehicle decelerates, and cooled air flows over the catalyst. This is considered to be due to the fact that the developed substrate is readily deprived of heat because its thermal mass is lower than that of the conventional substrate. However, because the temperature of the catalyst is much higher than light-off temperature in this domain, no effect on tail-pipe emissions was observed.

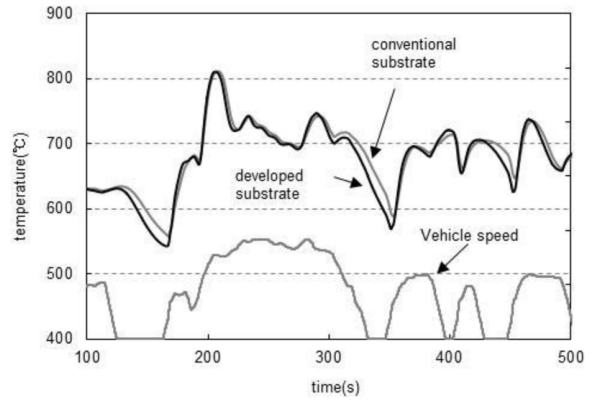


Figure 10. A comparison of the temperature of the close-coupled catalysts from 100sec to 500 sec in FTP mode.

Figure 11 shows transitions in temperature from the soak phase to engine restart and the of FTP mode. The decline in temperature during the soak phase is equivalent level. After restart, the catalyst temperature of developed substrate and conventional substrate is the same tendency as it does following cold start.

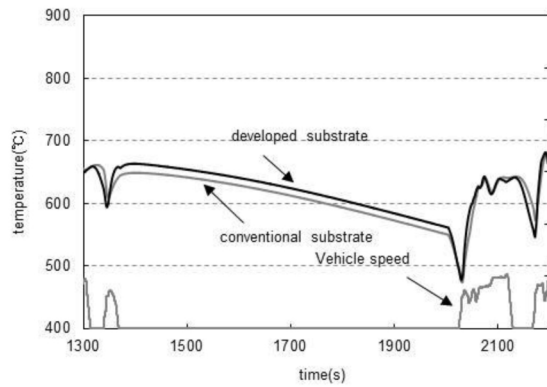
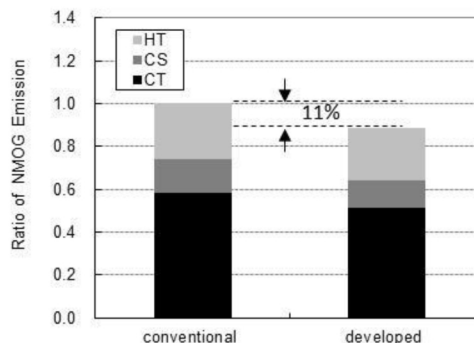


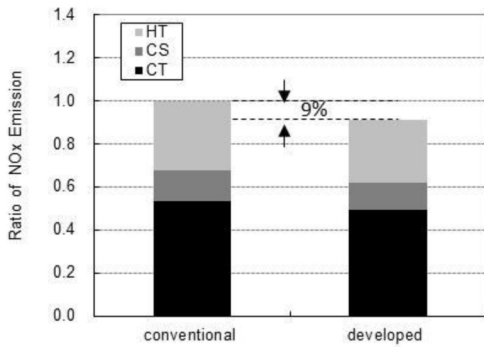
Figure 11. A comparison of the temperature of the close-coupled catalysts in soak phase of FTP mode.

Figure 12 compares measured tail-pipe emission (NMOG and NOx) value in FTP mode. CT in the figure 12 is for 505 seconds phase (bag1) after the FTP mode start, CS is for 505 seconds to 1368 seconds (bag2), and HT is for 505 seconds phase after re-starting(bag3). There was 9~11% improvement for the developed substrate than the conventional substrate. The results show that the developed substrate enables the catalyst to reach light-off temperature more quickly. These results can be considered to conform to the development concept.

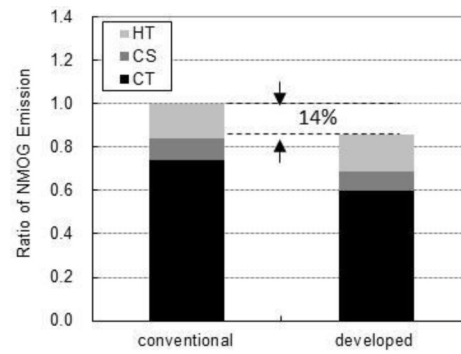


(a)

Figure 12. A comparison of (a) NMOG and (b) NOx in FTP mode.



(b)



(a)

Figure 12. (cont.) A comparison of (a) NMOG and (b) NOx in FTP mode.

The results shown in Figure 12 are for a specific engine exhaust layout, but changes in the effect of the developed substrate in different engines and with different exhaust gas temperatures and conditions can be predicted. When the temperature of the exhaust gas is extremely high, the catalyst reaches light-off temperature quickly irrespective of the weight of the substrate, and the effect that reducing the weight of the substrate could have on tail-pipe emissions should be minimal. By contrast, the effect of reducing the weight of the substrate can be predicted to be extremely large when the temperature of the exhaust gas is low. The future evolution of engines will undoubtedly proceed in the direction of increased thermal efficiency, and the temperature of exhaust gas will be reduced. From this perspective, it can be considered that a super-light substrate will have a significant effect. In order to examine the influence of lower exhaust gas temperature, a comparison in case of reduction in gas temperature at the time of vehicle start of FTP mode by shortening the first idle time was conducted. Figure 13 shows a catalyst temperature comparison with a standard test mode and low temperature mode test. The catalyst temperature at vehicle start was reduced approximately 150°C in both substrate. After vehicles start, the target velocity pattern of standard mode and low temperature mode is the same.

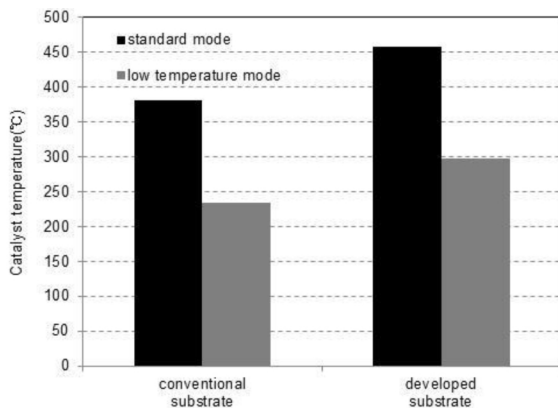
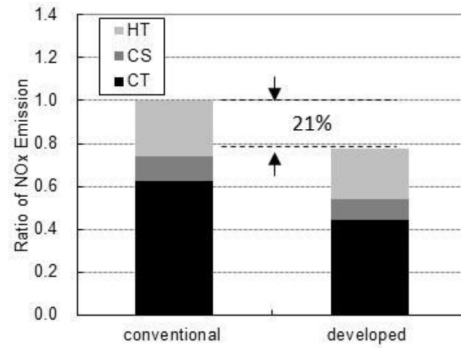


Figure 13. A catalyst temperature comparison with a standard test mode and low temperature mode test at vehicle start in FTP mode.

Figure 14 shows results for tail-pipe emissions in this low-temperature mode. There was 14~21% improvement for the developed substrate than the conventional substrate. The effect of the developed substrate was considerably higher than it was in tests using standard mode. It is considered to be the cause that the catalyst using conventional substrate has not reached light-off at vehicle start point in low temperature mode.



(b)

Figure 14. A comparison of (a) NMOG (b) NOx in low temperature test mode.

Summary

Regulations concerning automotive tail-pipe emissions will become more stringent in future, and a super-light substrate was developed to reduce these emissions. The developed substrate is 31% lighter than a conventional substrate while maintaining the same cell structure. The developed substrate shows the same pressure drop and thermal durability as a conventional substrate. Catalyst temperature and tail-pipe emissions were compared for the developed substrate and a conventional substrate in an actual vehicle. The speed of temperature increase was more rapid for the developed substrate than a conventional substrate. Tail-pipe emissions of FTP mode were reduced by 9~11%. It was also verified that the developed substrate will have a greater effect in reducing emissions when the temperature of the exhaust gas is lower.

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