$$\frac{P_d}{b} = \frac{\pi E}{2(1-\nu^2)} v_s \cos \alpha \cdot T_0 \times 10^3 \left[\beta(k_3) - 1.95 \times 10^{-2} \left\{ 2 \times 1.89 - \log_e \left(16 \frac{R}{b} \right) \right\} \right] \\ \times \left[\frac{1}{2} \frac{\pi b \cos^2 \mu_1}{(\gamma_1/g) A_{11}(x_0) l_1} \cdot \frac{ET_0^2}{2(1-\nu^2)} \left\{ 1 + \frac{\gamma_1 A_{11}(x_0) l_1}{\gamma_2 A_{12}(x_0) l_2} \cdot \frac{\cos^2 \mu_2}{\cos^2 \mu_1} \right\} \right]^{-\tau(k_3)} \quad (30)$$

In the above equation, the relations $E_1 = E_2 = E$ and $\nu_1 = \nu_2 = \nu$ are assumed, v_s is the velocity of impact, that is, $v_s = v \cdot \vartheta$, and v is the circumferencial velocity (m/sec) on the pitch circle; ϑ is a quantity called "Übersetzungsprung" by Olah⁽⁵⁾ and Schiebel⁽⁶⁾ and it depends on many kinds of errors of gear wheels; α denotes the pressure angle and R denotes the relative curvature of teeth at the contact point.

7. Conclusion

The author treated theoretically the dynamic load due to impact based on the assumptions that the impact occurs on one pair of teeth only. In the present paper, the author analysed this problem approximately by the collocation method and found out a design formula for dynamic loads based on some assumptions.

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Combustion of Coal by Gasification*

By Kensuke KAWASHIMO** and Kozo KATAYAMA***

Combustion of coal by gasification—transformation of coal into gas prior to combustion in a furnace—is an advantageous method of combustion especially for smoke-removal in cities and for utilization of low-quality coal, and can be applied for boilers, gas turbines and industrial furnaces.

Gas producers for this purpose must have improved efficiencies and high capacities. Construction and test results of a continuously operating gas producer, which was test-built to verify this method, are described and it is shown that this producer can be operated at a gasification efficiency (hot gas base) 94 % for a long period by employing an improved injection method of air and steam.

And, experimental results and technical problems about combustion of low-quality coal by gasification method are also discussed.

1. Introduction

From the standpoint of abolishing chimney-smoke in the cities and improving combustion of coal, particularly of low-quality coal, the writers wish to present a general summary of the test results of their intermediate commercial industrial usage of the equipment which has been developed from their basic experiments for the efficient combustion of coal by gasification⁽¹⁾⁽²⁾. Combustion of

coal by gasification—transformation of coal into gas prior to combustion in a furnace—has the following advantages:

(1) Complete combustion is gained with a minimum of excess air, as compared with the conventional combustion method of solid fuel. So combustion efficiency is increased and no smoke is generated in the exhaust gas.

(2) The produced gas does not carry any ashes; therefore no ash residue attaches itself on the heat transmission surface of boilers.

(3) Since the high temperature gas from the gas producer is burned immediately, high flame

* Received 9th May, 1960.

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temperature is obtained from a gas of lower heating value and the tar contained in the gas is also fully utilized in its vaporised state.

(4) In contrast with combustion of coal on the fuel bed or of pulverised coal, the process within the gas producer has the advantage of being able to control strictly the output of the produced gas, the gasification temperature, the condition for injecting (by increased flow speed) the gasifying agents (air and steam), and removal of ashes, and so the combustion of low-quality coal, impossible by any other process, becomes practicable by this method.

The gas producers for the combustion of coal by gasification must be different from the past prototypes on the following points.

(1) They must have an increased gasification capacity and an improved gasification efficiency (the gas compositions are secondary problems and emphasis should be placed on the combustion efficiency).

(2) Continuous operation is essential and they must be operated easily.

(3) Besides coal for gas-producer of medium size, all kinds of coal for usual purposes, as well as powder or medium-size coal or extremely low-grade cheap coals can be used.

In this paper, a continuous gas producer for the combustion of coal by gasification, which was test-built, and its main characteristics are described, and the test results show that this equipment has enough capacity to fulfill the necessary condition of the gas producer for combustion of coal described above. To show the engineering problems in application of this method for combustion of low-quality coal, a fundamental study of gasification of low-quality coal is briefly described. This method of combustion of coal is intended for application to boilers, gas turbines and industrial furnaces.

2. The continuous operating gas producer for combustion of coal by gasification

2.1 Description of the continuous operating gas producer which was test-built

The process of combustion of coal by gasifica-

Fig. 1 Process diagram of the combustion of coal by gasification

Fig. 2 Continuous operating gas producer which was test-built

tion is shown by a process diagram in Fig. 1. Coal which is stored in a hopper at the top of the producer is fed into the producer with a rotary-type coal feeder, and is gasified with the air from a turboblower and with the steam from a cooling jacket surrounding the producer and an outside steam boiler.

Produced hot gas flows out from the upper part of the producer and, after removing coal dust with a cyclone separator, is burned in a furnace with secondary air.

The assembly map of the gas producer used for the pilot-plant test of this method is shown in Fig. 2. And Figs. 3 and 4 show the view of the producer and the rotary-type coal feeder. The specifications of the plant are shown in Table 1.

The gas producer, welded of steel plate, has a dodecagonal cross section of inner diameter 800 mm, which form is chosen following the 12 air injection nozzles, and is surrounded with a water jacket where some portion of steam for gasification is produced.

The lower part of the producer wall is rotated to assure uniform drop of coal-layer in the producer. At the center of the bottom of the producer, there

is a rotary grate of hexagonal form to crash clinkers. Ash drops through this grate into an ash-trough and is carried outside by a screw-conveyor and a dragchain-conveyor.

2.2 The main characteristics of this gas producer

This gas producer aimed at the generation of gas for combustion contains the following characteristics: the process of air-injection and the removal of clinker troubles.

At the upper part of the coal layer in the gas producer, coal is preheated and is distilled by hot gas, where flowing velocity of gas should be kept low to prevent carry-over of coal dust. On the other hand, at the lower part of coal layer, gasification reaction of semi-coked coal occurs. This heterogeneous reaction can be improved by increasing the injection speed of gasifying agent—high velocity gasification⁽²⁾.

So, by injecting the gasifying agent tangentially from the producer wall with high velocity, we can improve specific coal gasification rate and reduce thickness of coal layer by minimizing the carry-over of coal dusts. Following this principle, we developed

Fig. 3 Gas producer which was test-built

Fig. 4 Rotary coal feeder at the top of the producer

Table 1 Specification of the continuous-operating gas producer which was test-built

Size of the gas producer	: Inner diameter×Height, 800 (dodecagonal cross section)×1400 mm. Actual cross sectional area 0.50 m ² .
Blower	: Capacity 1000 N m ³ /hr. Pressure 1200 mmAq. Driving electric motor 10 H.P. (7.5 kW).
Coal feeding equipment	: Rotary coal feeder; Capacity 120~360 kg/hr, driving motor 1/2 H.P. Bucket coal conveyor; Max. capacity 1000 kg/hr, driving motor 2 H.P.
Ash removing equipment	: Rotary grate: Capacity 300~120 kg/hr, driving motor 2 H.P. Drag-chain conveyor; Capacity max. 200 kg/hr.
Gasification capacity	: 120~360 kg/hr.
Coal gasification rate	: Max. 500 kg/hr.
Pressure of gasification	: 0.10 kg/cm ² (gauge)

a new type gas producer.

The air for the generation of gas is fed from two directions: One-third of the air is injected upward through the bottom rotary grate in order to

Fig. 5 Combustion of the produced gas in a furnace

Fig. 6 Flow-quantity, heating-value, and temperature of the produced gas, and flow-quantity of the gasification air during the test

diminish the combustible content in the ash, and the remaining two-thirds of the air are fed tangentially through the furnace wall at a high speed of 72 ~ 50 m/sec maximum to form a spiral flow within the producer. The 12 injection nozzles for the latter are divided into three groups of four nozzles spaced at 90° each. Each group can be manipulated individually and the gasification agent can be distributed uniformly in the producer, thus achieving uniform distribution of temperature within the producer.

This process prevents the carry-over of coal dusts and increases the gas-generation capacity by minimizing the thickness of the coal layers, as well as diminishing clinker troubles and increases the gas-generation efficiency by assuring reaction be-

tween the continuously injected steam and overheated coal layers.

This producer prevents the formation of stratified clinker by a continuous injection of steam, and the localized clinker is ejected after being crushed. The bottom of the generator consists of a revolving wall and a hexagonal rotary grate containing air inlets, and they revolve diametrically. The clinkers are crushed by the six corners of the rotary grate and the resulting ash is dropped through the spaces of the six corners into a waterpool type ash-trough.

Since the generated gas which has a temperature between 500~700°C is burned immediately in the boiler-furnace, the tar elements are still dis-

Table 2 Test results of the gas producer

Type of coal used	: Powder coal from Mitsubishi Bibai Coal Mine, Hokkaido, Japan.					
	Proximate analysis	Moisture	Water	Ash	Volantile matter	Fixed carbon
	%	3.02	3.63	19.37	34.91	42.09
	Heating value of the coal : 6170 kcal/kg.					
Duration of the test	: 12.20~20.00 (7.67 hrs).					
Amount of coal gasified	: 1125 kg.					
Coal gasification rate	: 147 kg/hr or 3.52 ton/day.					
Specific coal gasification rate	: 294 kg/m ² hr.					
Amount of gasification air	: 350 Nm ³ /hr (2.83 Nm ³ of air per 1 kg of coal).					
Output of produced wet gas	: 525 Nm ³ /hr (472 Nm ³ /hr in dry gas).					
Produced gas temperature	: 500°C (Heat content of the produced dry gas is 202 kcal/Nm ³).					
Output of produced gas per 1 kg of coal	: 3.64 Nm ³ /kg.					
Produced gas composition	CO ₂	CO	H ₂	CH ₄	O ₂	N ₂
	Vol. %	7.5	13.9	22.9	1.9	52.4
Heating value of produced dry gas*	: 1585 kcal/Nm ³ .			Gasification efficiency (cold gas base) : 83.3 %*.		
Heating value of produced wet gas*	: 1438 kcal/Nm ³ .			Gasification efficiency (hot gas base) : 93.9 %*.		

* Heating value of the produced gas is measured by a continuous gas calorimeter after cooling and removing tar contained in the hot produced gas. In these data the calorific values of the tar in the hot produced gas are not included.

integrated in a vaporized form, and are fully utilized; thus no smoke is to be detected in the stack.

2.3 Test results of the gas producer which was test-built

A typical test result with this new type gas producer for the combustion of coal by gasification is shown in Table 2. The coal used is a powder-coal from Bibai Coal Mine, Hokkaido, Japan.

In the test, except immediately after the starting of the test, the coal-feeding and the steam-feeding were controlled in order to maintain a stable condition of air-feeding and the produced gas-temperature, and this was continued for more than ten hours during which the gas properties, gas quantity, the specific coal gasification rate and the gasification efficiency were measured. For the measurement, in the case of air and gas quantities, the JES 358 orifices were used, and in the case of gas-heating value, the continuous recording type gas calorimeter of Inao Electric Co.; and in the case of gas properties the gas chromatography was primarily used.

Fig. 6 shows the gas quantity, heating value, and the gas temperature during the test period shown in Table 2, while Fig. 7 shows the heat balance diagram taken from the test results. The gas heating value is measured by a continuous gas calorimeter after water-cooling the generated gas of 500°C, and removing the tar vapors, therefore, it does not include the heating-value of the tar properties in the gas. As the heating value of the tar could not be measured, this value was estimated as a loss with the heating value of unburned coal in the heat balance shown in Fig. 7. So net effi-

ciency of gasification is considered to be actually better.

2.4 Discussion of the test results

In gasification reaction, the following reactions are known, in the oxidization zone,

in the deoxidization zone,

In these reactions, if the reaction temperature is assumed, the produced gas quantity, gas composition, heating value of the produced gas can be calculated, but the reaction constants necessary for the calculation is affected by the reaction temperature⁽³⁾⁽⁴⁾.

Here, the authors compare the composition of the produced gas from their test results with the calculated results with diagrammes made by Prof. Bošnjaković⁽⁵⁾.

Fig. 8 shows relations between reaction temperature, combustible gas composition and the molar ratio ψ of steam in the gasifying agent. And Fig. 9 shows the change of gas composition by adjusting the reaction temperature with steam. These calculations are assumed to be the reaction

Fig. 7 Heat balance diagramme from the test result shown in Table 2

Fig. 8 Variation of gasification temperature and volumetric fraction of H_2 and CO in the produced gas by molar fraction of H_2O ψ in gasification agent⁽⁵⁾. Injection temperature of the gasification agent $t' = 100^\circ\text{C}$

of carbon by neglecting the formation of methane, and the temperature of gasifying agent is assumed to be 100°C.

In the authors' the molar ratio of steam ψ was kept $\psi=0.2\sim0.3$, and the gasification temperature was 650~750°C. We see that the concentration of H_2 and CO_2 practically coincide with the measured value, and that the test-value of CO is lower than the calculated value. The latter is due to the pre-

Fig. 9 Variation of calculated volumetric fraction on produced gas composition when gasification temperature t is controlled by injection of steam⁽⁵⁾. Injection temperature of the gasification agent $t'=100^\circ\text{C}$

sence of non-uniform thickness of coal-layer in the producer, and more efficient gasification can be expected by eliminating the defects.

Fig. 10 shows the relationships between the

- Type of fuel:
- 1 pressed peat (Presstorf)
 - 2 low-temp. coke from brown coal briquette. (Braunkohlen Brikette-Schwelkoks)
 - 3 anthracite (Anthrazit)
 - 4 hard coke from brown coal (Braunkohlen-Hartkoks)
 - 5 middle-temp. coke from bituminous coal (Steinkohlen-Mittel-temperaturkoks)
 - 6 low-temp. coke from bituminous coal (Steinkohlen-Tieftemperaturkoks)
 - 7 high-temp. coke from bituminous coal (Steinkohlen-Hochttemperaturkoks)
 - x present test result

Fig. 10 Relation of specific gasification capacity to net heating value of produced gas and gasification efficiency (cold gas base) for various fuels by Wolschlager⁽⁶⁾

Table 3 Comparison of the present test results with those of typical gas producers

Type of gas producer	Present test results	Wellman-type ⁽⁷⁾	Wood SB 10 ⁽⁷⁾⁽⁸⁾	Wilson-type ⁽⁸⁾	A Germany producer ⁽⁹⁾
Size of producer inner diameter × Height in m	0.80 × 1.4 dodecagonal	3.05 × —	3.05 × 2.90	2.14 × 3.50	1.30 × 1.20
Capacity ton/day	8.5	30	60	9.4	—
Coal gasification rate kg/hr	147	875	2 260	302	—
Specific coal gasification rate in kg/m²hr	294	120	315	84.0	—
Type of coal	Bibai	Hōjō	Akaike	Yorkshire	—
Heating value of coal kcal/kg	6 170	—	6 321	7 642	—
Amount of gasifying air Nm³/hr	350	1 400	4 500	957.9	—
Output of produced gas Nm³/hr	525	—	8 250	1 271.6	—
Produced gas temperature °C	500	500~650	720~740	674	—
Gas composition: vol. % CO ₂	7.5	6.14	4.2	6.9	5.0
CO	13.9	23.33	27.0	23.2	20.0
H ₂	22.9	13.16	12.5	11.6	13.0
CnHm	—	0.66	—	0.42	—
CH ₄	1.9	4.93	4.0	4.68	1.5
N ₂	52.4	50.74	54.0	53.2	60.5
Heating value of produced gas in kcal/Nm³	1 438	—	1 446	1 365	1 300
Gasification efficiency					
in cold gas base %	83.3	—	84	about 70	80
in hot gas base %	93.9	—	—	about 80	—

specific gasification capacity ($\text{Nm}^3/\text{m}^2\text{hr}$), the gasification efficiency of cold gas base, and gas net heating value developed by Wohlschläger⁽⁶⁾ for various types of fuels. According to the test results shown in Table 2, the specific gasification capacity of the producer $1070 \text{ Nm}^3/\text{m}^2\text{hr}$, the gasification efficiency of cold gas base 83.3 %, the gas net heating value 1438 kcal/Nm^3 surpass the corresponding values for the past gas-producer.

Table 3 represents a comparison of the present test results and the working results of other typical gas producers. The gas-producers usually improve their efficiency as they grow in size⁽¹⁰⁾, but the equipment under consideration despite its small size, equals in efficiency a large one of a capacity of 60 tons/day. This performance is due primarily to the fact that the gasification agents is injected tangentially from the wall of the producer at a high speed. And, in the case of pregenerated gas combustion, it is possible to burn a generated gas of $500\sim 700^\circ\text{C}$ without cooling, and so the gasification efficiency 93.9 % of hot gas base including the heat content of the generated gas is essential in the practical usage of the process.

The ignition of the produced gas was better than the ordinary producer gas and one of the advantages of this method of combustion of coal — no spoiling and no corrosion on the heat transmission surfaces — was also certified by this test.

From the above comparisons, the test results of the authors' gas producer which was test-built are shown to meet the necessary conditions of gas producer for combustion of coal by gasification. In conclusion it can be asserted that there is an unlimited possibility of the practical application of this method.

3. The combustion of low quality coal by gasification

3.1 The problems attending the gasification of low quality coal

When utilizing low-quality coals as a source of heat-energy, gasification is a worthwhile method. In a country like Japan where both the production and the grade of coal are low, the exploitation of

the low quality coal, which accounts for 25 % of the total production⁽¹¹⁾, is greatly significant in the rationalization of the coal mines.

With the idea of industrial application in mind, the writers wish to illustrate the technical problems attending the gas producers utilizing a low quality coal. The results gained from a small experimental gas-producer of the actual cross sectional area 0.14 m^2 are shown. The low quality coal thus tested received no preliminary processing such as selection of coal size, drying or crushing in view of the ultimate industrial use of the test. They were low-quality coals (net-heating value 2 670 and 1 650 kcal/kg, ash-content 61.5 and 70 %) from the Yubetsu Coal Mine, Hokkaido, Japan. The test results are shown in order to give a picture of the technical problems attending the gas-producer using a low-quality coal.

Fig. 11 Experimental gas producer for the test of low quality coal

Table 4 Analysis of low quality coals tested

Coal	Proximate analysis %				Heating value kcal/kg	Ash soft temp. °C	Ash melt temp. °C	Ash flow temp. °C	Average size mm
	Moisture	Ash	Volatile matter	Fixed carbon					
Tested Yubetsu (1)	6.0	61.5	24.0	8.5	2 670	1 245	—	—	<30
Tested Yubetsu (2)	5.70	65.86	18.49	9.95	1 669	1 160	1 250	1 320	<30
Shinnyu	2.64	43.13	28.34	25.90	4 160	1 280	1 430	>1 450	15~50
Takamatsu	3.84	60.44	21.37	14.35	2 600	>1 450	—	—	15~50

In contrast to the problem of removing the water content in the case of lignite, the problem with low quality coals is primarily related to the handling of the 50 to 70 % ash-content, clinker, and ash removal.

3.2 Summary of the test

The qualities of the low quality coal used in the test are shown with other typical low-quality coals in Japan in Table 4.

Yubetsu low-quality coal (2) shown in Table 4 is powdery, and contains a high percentage of white-coloured ash when dry; and when wet it becomes muddy, and is extremely difficult to crush or to handle. In this test an experimental gas producer of the actual cross sectional area 0.14 m^2 as shown in Fig. 11 was used, and the air injection method was the same as the one noted previously.

The test⁽¹²⁾ involved measurements of the generated gas composition and the coal gasification rate by changing the air-intake quantities with two types of low-quality coals of 2 670 and 1 669 kcal/kg respectively. In this way, the best conditions for gasification were discovered. The test results are shown in Fig. 12 and 13.

In this test, neither the gas calorimeter nor the gas chromatograph could be used, and so the gas heating-value was assumed from the CO and H_2 content derived by the MONO gas analyser. Therefore, the gasification efficiency couldn't be determined.

When we observe the experimental results, we note that the specific coal gasification rate rises with an increase in the air-intake quantities, but the gas compositions attain a maximum of combustion gas composition at a definite air-intake quantity, which is the best air-quantity for that type of coal and the producer. This value is 1.2 ~ 1.4 times the air quantity noted by theoretical calculation for gasification.

In every test, combustible gas was generated 3

~5 minutes after firing, and in its gas composition, combustion properties and the flames were as stable as the gas generated from an ordinary coal. There was not the least evidence of carry-over of coal dusts and blockage of pipes by tar. Therefore it can be claimed that there are no technical problems arising in the gas burners from the use of a low-quality coal.

Summary of the gasification test using the low-quality coal.

1. The same degree of gas-combustion as achieved from an ordinary coal is attained from a low-quality coal of ash-content 60~70 % and net heating value 2 670~1 650 kcal/kg. Since there are no tar problems and smoke attending the process, it can be used with boilers and gas-turbines.

2. The process of injecting the intake air from the outer perimeter of the producer tangentially at a high speed is highly effective in raising of specific coal gasification rate and in the prevention of partial burning.

3. The most important technical problem in gasification of a low-quality coal is the method of ash handling. And, it is necessary to develop an equipment powerful enough to crush and remove clinkers. A typical example of this is shown in Fig. 14.

The problem of utilizing low-quality coal is being studied in various countries by a variety of methods, but in the case of low-quality coal with an ash-content of 50 % or more, the cost of pulverizing and selecting of coal size and the price of the equipment needed are so high as to make its use un-economical. Therefore, methods of combustion by pulverized coal or by the fluidized gasification are considered impractical.

The process of combustion of produced gas from a low-quality coal, as compared with other equipments for the combustion of a low-quality coal, has

Fig. 12 Experimental result of gasification by Yubetsu low quality coal (1) shown in Table 4. Heating value of the coal 2670 kcal/kg, ash 61.5 %

Fig. 13 Experimental result of gasification by Yubetsu low quality coal (2) shown in Table 4. Heating value of the coal 1669 kcal/kg, ash 65.9 %

very little limitations in the scope of its application. When we take note of the fact that the generated gas can be used in the same way as the ordinary produced gas, we become aware that the low-quality coal can be fully used as fuel in the conventional boilers and the combustion equipment, when the combustion by gasification method is used.

4. Summary

Gas producers for the combustion of coal by gasification must have an improved gasification efficiency and must have a large capacity of gasification in spite of their small size. As results of the industrial test conducted with the pilot plant of the continuous operating gas producer for this purpose, it was found that powder-coal could generate continuously for a long period at specific coal gasification rate of $300 \text{ kg/m}^2\text{hr}$, and gasification efficiency (hot gas base) of 94 % employing method of injecting the gasification agents (air and steam) at high speed from the two directions of the generator wall and the bottom grill respectively so that a spiral flow takes place. So it was verified that gas producers of such a type could satisfy the necessary condition of gas producer for combustion of coal by gasification.

Furthermore, in the authors' gasification experiment of low-quality coal with an experimental gas-producer, it was found that the low-quality coal of 60 % ash-content and heating-value 2500 kcal/kg can be successfully used from the technical standpoint, and also that even with such a low-quality coal of 70 % ash-content and heating-value 1500 kcal/kg the combustion by gasification is possible. In order to enlarge the gas producer for the purpose of combustion by gasification of low-quality coal, the problem of ash removal is most important, but this is possible by increasing the revolving speed of the rotary grate.

The future problem of combustion of the low-quality coal by gasification is that of electric-generation by gas turbine with high-pressure gas of $5 \sim 10 \text{ kg/cm}^2$, but when we consider the technical problems with the above experiments as a basis, it seems that they can be solved in the near future.

This method of combustion of coal is not only advantageous from the standpoint of heat economics but also from that of an aggressive attack on the problem of smoke-removal in the cities, and at the same time, this method can be utilized to exploit the low-quality coals, which have been left untouched as valueless, for the generation of power, or for synthetic gas, for the purpose of operating coal mine electric-generators, or for the chemical

Fig. 14 Rotary grate at the bottom of the gas producer, which can crush clinker. Holes to inject air can be seen at the top

industries, and they will ultimately contribute to the lowering of coal-cost and to the utilization of a new energy source.

This work was conducted at the Department of Mechanical Engineering, Tokyo Institute of Technology, as a graduation research of the students from 1956 to 1959, and the writers express their thanks to the graduates and Mr. Saito of the laboratory for their contributions. At the same time, they wish to express their thanks to the Mitsubishi Mining Co. and Yubetsu Coal Mining Co. for sending them coal samples, and to Mr. Horiye, President of the Daito Industry Works Co., and his employees for their cooperation in constructing their test plants.

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