MONITORING THE EFFICIENCY OF COOLING AIR AT THE INLET OF GAS ENGINE IN INTEGRATED ENERGY SYSTEM

by

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The fuel efficiency of gas engines is effected by the temperature of intake air at the suction of turbocharger. The data on dependence of fuel consumption and engine electric power on the intake air temperature were monitored for Jenbacher gas engine JMS 420 GS-N.LC to evaluate its influence. A waste heat of engine is rejected for heating water to the temperature of about 90 °C. The heat received is used in absorption lithium-bromide chiller to produce a cold in the form of chilled water. A cooling capacity of absorption chiller firstly is spent for technological needs and then for feeding the central air conditioner for cooling the ambient air incoming the engine room, from where the air is sucked by the engine turbocharger. The monitoring data revealed the reserves to enhance the efficiency of traditional cooling system of intake air by absorption chiller through deeper cooling. This concept can be realized in two ways: by addition cooling a chilled water from absorption chiller to about 5-7 °C for feeding engine intake air cooler or by two-stage cooling with precooling ambient air by chilled water from adsorption chiller, in the first stage and subsequent deep cooling air to the temperatures 7-10 °C in the second stage of intake air cooler by using a refrigerant as a coolant. In both cases the ejector chiller could be applied as the most simple in design.

Key word*s: engine, intake air cooling, absorption chiller, ejector chiller*

Introduction

Integrated energy systems (IES) driven by gas engines for combined cooling, heat and electricity supply received a widespread application [1, 2]. The gas engines, are manufactured as cogeneration modules with heat exchangers [3, 4] to reject the heat from lubricating oil, engine jacket cooling water, scavenge air and exhaust gas to produce hot water with temperature of about 90 °C. A hot water is used as a heat source for absorption lithium-bromide chiller (ACh) [5, 6] or adsorption chiller [7, 8] to produce a cold in the form of chilled water. A cooling capacity of absorption chiller is spent for technological needs and for feeding to the central air conditioner for cooling the ambient air incoming the engine room, from where the air is sucked by the engine turbocharger (TC) [9, 10]. The peculiarity of IES that supply chilled water for food processing is its higher temperature of about 12 °C as compared with 7 °C typical for ACh. The use of water with a temperature of 12 °C as a coolant is not able to manage a stabilized low temperature of air at the intake of engine and provide its high fuel efficiency.

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Deeper engine intake air cooling is possible by using a refrigerant as a coolant for engine intake air cooler. For this purpose the ejector chiller (ECh), the most simple in design, might be applied as an additional low temperature chiller. In order to approve the expediency of such decision the data on influence of intake air on engine fuel efficiency are needed. They can be received by treating the monitoring data on engine fuel consumption at varying engine cyclic air temperature and power loading.

The goal of investigation is to evaluate the efficiency of cooling air at the intake of gas engine driving the IES by treating the monitoring data on dependence of fuel consumption and engine electric power as basis to develop decisions for its improvement, providing an enhancement of fuel efficiency of the engine.

Literature review

There are a lot of waste heat recovery technologies developed to enhance a fuel efficiency of combustion engines: by utilizing the exhaust heat [11, 12] and cooling engine cyclic air (intake and scavenge air) in electrically driven vapour-compression refrigeration machines [13, 14] and waste heat recovery chillers [15, 16]. The most widespread ACh enable cooling air to the temperature of about 15 ºC with a high coefficient of performance: *COP* = 0.7-0.8 [17, 18]. The vapour-compression chillers provide cooling air practically to any low temperature but at the expense of consuming the electricity to drive the compressors [19, 20]. The refrigerant ECh are the most simple in design and able to provide cooling air to the temperatures of 5-10 ºC but with low *COP* = 0.2-0.3 [21, 22].

The efficiency of refrigeration chillers and the whole cooling systems can be increased through intensification of heat transfer in heat exchangers [23, 24] first of all of refrigerant boiling in evaporators [25, 26] and by application of advanced coolant (refrigerant) circuits with injector [23, 27], evaporative [28, 29] and two-stage cooling [30] with heat conversion in combined chillers [31].

The energy saving technologies with accumulating cooling capacity at decreased thermal loads on the engine cyclic air cooling systems as well as for air conditioning systems to cover peak thermal loads are developed [31].

Many researches focused to improve the operating efficiency of cooling systems in the actual site climatic conditions [32, 33], optimization of air conditioning systems [34, 35] and to develop the methods of their rational designing [36, 37].

The majority of concepts and approaches to enhancing the efficiency of IES focuse to application of cooling capacity generated in ACh for external consumers, for instance, for space conditioning and technological duties [38]. They do not reveal the reserves for improving the efficiency of cooling the cyclic air of engines themselves and enhancing the engine-generator technologies in the whole as result through using the generated cooling capacity within engine cycles [10, 17].

In order to approve the approach of enhancing the fuel efficiency of gas engine driving the IES, the data on influence of intake air temperature on engine fuel efficiency are needed. They can be received by treating the monitoring data on engine fuel consumption at varying engine intake air temperature and loading.

Research methodology

The efficiency of cooling air at the intake of gas engines was investigated for IES of the enterprise *Sandora – PepsiCo Ukraine*. The IES includes two cogeneration modules based on Jenbacher gas engines JMS 420 GS-N.LC (rated electric power $P_{e\mathrm{ISO}}$ = 1400 kW, heat power

Q_h =1500 kW). The heat rejected from lubricating oil, engine jacket cooling water, scavenge air-gas mixture and exhaust gas is converted in AR-D500L2 Century Ach to produce a refrigeration in the form of chilled water with a temperature of 12 °C. The refrigeration capacity is spent to cover the technological cooling needs and for feeding to the central air conditioner intended for cooling the ambient air incoming the engine room, from where the air is sucked by the engine TC, fig. 1.

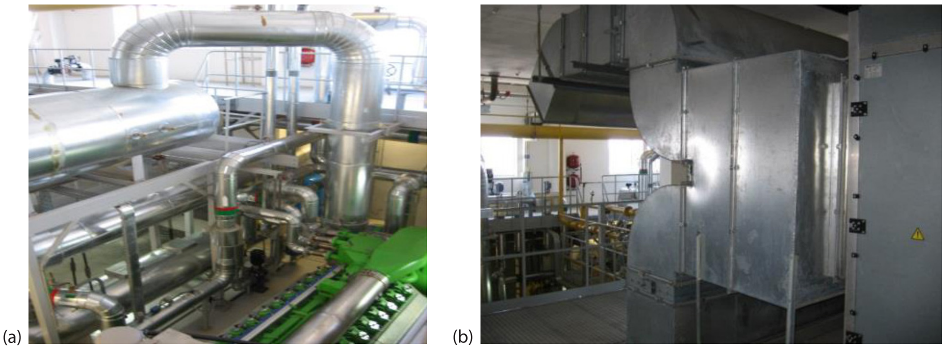


Figure 1. Cogeneration gas engine module (a) and central conditioner for cooling the ambient air, coming into the engine room (b) of IES at the enterprise *Sandora – PepsiCo Ukraine*

A typical waste heat recovery system of gas engine module based on ACh is shown in fig. 2.

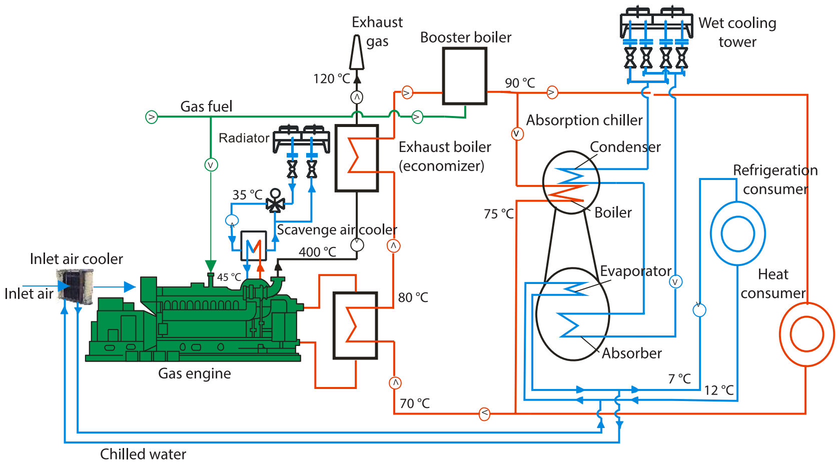


Figure 2. Typical waste heat recovery system of cogeneration gas engine module based on ACh

A method for treating the monitoring data on fuel consumption depending on the air temperatures at the engine intake with regard to the influence of changes in engine loads was presented in [10, 30]. That method is modified by using for treatment of monitoring data the correlations from the generalized methodology presented in [39].

The purpose of treating the data sets on full volume fuel consumption, G_f, and electric power, P_el, is to find the data on specific volume, b_f, or mass, b_e, fuel gas consumption, *i.e.* full fuel consumption related to electric power, in dependence on the engine intake air temperature, t_in, to estimate the efficiency of engine intake air cooling at varying loading.

It should be noticed that the correction coefficients received by authors in calculation correlations are supposed to be valid for treating the monitoring data of gas engines JMS 420 GS-N.LC as driving engines operating in a concrete IES.

The method of treating the monitoring data is based on their statistical analysis by sampling the monitoring data on engine full volume fuel consumption as a function of intake air temperature, t_{in}: $B_f = f(t_{in})$ at varying engine electric power, P_{el}.

A time interval of measurements in a stable mode was τ = 1-30 seconds, a number of measurements in a stable mode – 8-240.

Monitoring data sets $B_f = f(t_{in})$ and $P_{el} = f(t_{in})$ were formed at different engine loading $P_{el}/P_{el.ISO}$ = 0.6-1.0, where P_{el} and $P_{el.ISO}$ are the actual engine load and nominal engine load rated at ISO parameters [39].

The main measurement devices and their ranges of measurements and accuracy are indicated in tab. 1.

Table 1. Measurement devices

Parameter	Measurement device	Range of measurements	Accuracy class, error
Relative humidity of air	Sensor of humidity and temperature – DVT-01 (*RegMik*)	0-100%	± 2%
Temperature of ambient air		–40-120 °C	± 0.5 °C
Temperature of intake air	Temperature sensor – TSMU-0124 (NPF *RegMik*)	0-120 °C	± 0.5 °C
Volume flow of fuel gas	Ultrasonic gas meter – KURS-01 G250 A1	1.6-400 m^3 per hour	± 1%
Electric power	Electricity meter SL 7000 Smart (SL761)	1-120%	± 0.5%

As an example, the magnitudes of errors in determining the engine volume fuel gas consumption within the confidence interval P = 0.95 for measurements conducted in July 2019 are shown in tab. 2.

The error of experimental data was determined by taking into consideration the error of measuring instruments, methodological and systematic errors and was about 5-6%.

Table 2. The values of errors in determining the consumption of engine volume fuel gas B_f

Volume consumption of fuel gas	Relative errors			
	Systematic errors	Confidence probability P = 0.95	Confidence interval	Overall relative errors including methodological errors
B_e, [m^3 per hour]	$\Delta B_f/B_f$	$\Delta B_f/B_f$	B_f, [m^3 per hour]	$\Delta B_f/B_f$
359.1	0.0090	0.0004	1.10	0.049
359.3	0.0098	0.0006	1.70	0.050
358.2	0.0091	0.0004	1.20	0.050
356.1	0.0091	0.0002	0.70	0.049
361.4	0.0093	0.0020	5.70	0.051
360.5	0.0104	0.0012	3.30	0.052

The results of monitoring fuel efficiency of GE JMS 420 GS-NL were presented in the form of data sets on dependence of full volume fuel consumption $B_f = f(t_{in})$ and engine electric power $P_{el} = f(t_{in})$ on the air temperature, t_{in}, at the intake of engine at varying loading.

The monitoring values of specific volume fuel consumption, b_f, was determined by full volume fuel consumption, G_f, and electric power output, P_{el}: $b_f = G_f/P_{el}$, m^3/kWh, or specific mass fuel consumption $b_e = b_f \rho_f$, where $\rho_f = 661.7$ g/m^3 is the mass density of gas fuel.

The calculation values of specific mass fuel consumption, b_e, was determined by correlation according to generalized methodology presented in [39]:

$$b_e = b_{e,\,ISO}\left(\frac{P_{el}}{P_{el,\,ISO}}\right)^{-0.1015}\left(\frac{T_{in}}{T_{in,\,ISO}}\right)^{0.443} \tag{1}$$

where $P_{el,ISO}$ = 1420 kW, $T_{in,ISO}$ = 298.15 K ($t_{in,ISO}$ = 25 °C), $b_{e,ISO}$ = 167.764 g/kWh, and 0.443 and –0.1015 are correction coefficients received by authors during treating the monitoring data of gas engine JMS 420 GS-N.LC.

The results of comparison of calculation values of specific mass fuel consumption, $b_{e.calc}$, with monitoring data, $b_{e.monit}$, are presented in fig. 3.

As fig. 3 shows, a deviation of calculated values of mass specific fuel consumption $b_{f.calc}$ from their monitoring data $b_{f,monit}$ is about 5-6 %, that proves a satisfactory their agreement.

With this a sample of number of points, n/N, corresponding to the approximation with a relative error of not more than 5% was about 95%.

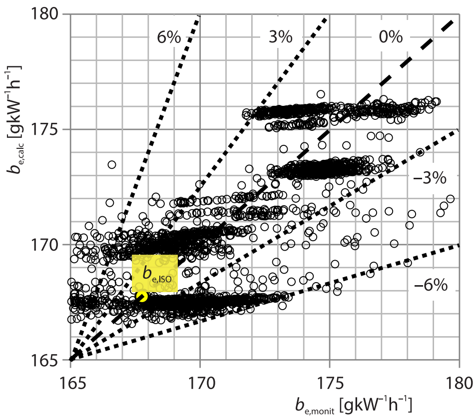


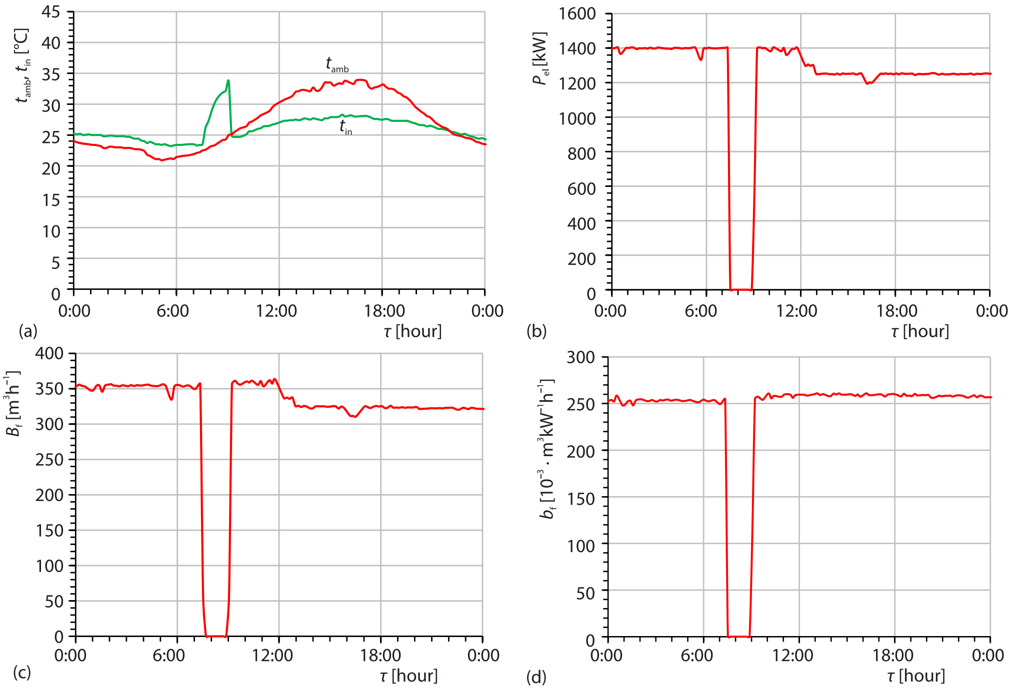
Figure 3. The calculated values of mass specific fuel consumption, $b_{e,calc}$, against their monitoring data, $b_{e,monit}$: point $b_{e,ISO}$ corresponds to ISO climatic parameters [39]

Results

A sample of results of monitoring daily changes of full volume gas fuel consumption, B_f, and electric power, P_{el}, of gas engine JMS 420 GS-N.LC and specific volume $b_f = B_f/P_{el}$ and mass $b_e = b_f \rho_f$ fuel consumption in June are presented in fig. 4.

As fig. 4(a), a shows, within time interval τ = 7-9 hours, when the engine was switched off, fig. 4(b) and ACh did not feed a chilled water with a rate temperature of 12 °C to the air conditioner for cooling ambient air incoming the engine room, the temperature of the air at the intake of engine, t_{in}, is raised sharply by about 10 °C higher than the ambient temperature, t_{amb}. This air temperature increment reflects an increase in the temperature of incoming ambient air caused by heat influx from surroundings in the engine room. As a result of the last, a temperature of the air at the intake of engine, t_{in}, remained at increased level during the most daily time after τ = 10 hours, when the engine was switched on, fig. 4(b) and the air conditioner consumed a chilled water from ACh with temperature of 12 °C. This causes increased specific fuel consumption b_e of about 168 g/kWh compared with 165-166 g/kWh in the night and morning hours before τ = 7 hours, fig. 4(d).

The results of treating the monitoring data on the engine electric power $P_{el} = f(t_{in})$, full volume fuel consumption $B_f = f(t_{in})$ and specific mass fuel consumption be in dependence on temperature tin of air at the intake of engine JMS 420 GS-N.LC at the loads P_{el} = 900-1400 kW (the values within the range $P_{el}/P_{el,ISO}$ = 0.6-1.0 related to ISO point [39]) are presented in figs. 5-7.



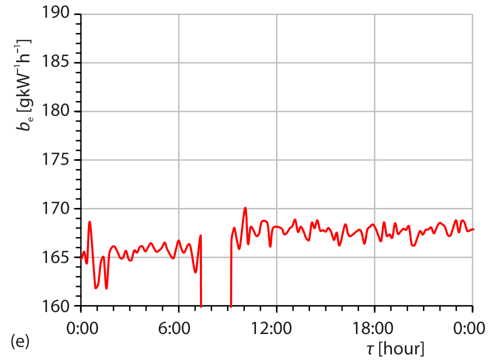


Figure 4. Daily changes in the ambient air temperature, t_{amb}, and engine intake air temperature, t_{in}, (a), engine electric power, P_{el}, (b), total volume fuel consumption, B_f, (c), volume, b_f, (d), and mass, b_e, (e) specific fuel consumption *vs.* time, τ, (July)

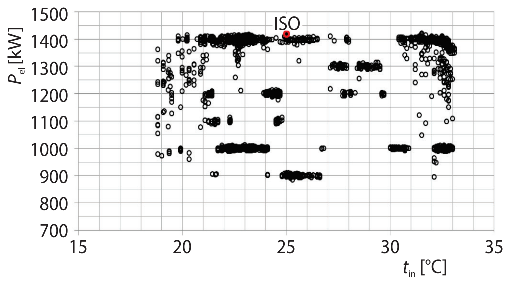


Figure 5. The values of electric power, P_{el}, in dependence on the temperature, t_{in}, of air at the intake of engine JMS 420 GS-N.LC at the loads P_{el} = 900-1400 kW

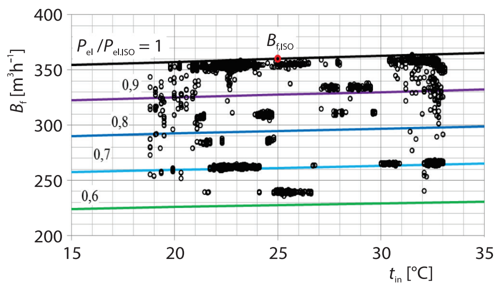


Figure 6. The values of full volume fuel consumption, B_f, in dependence on the air temperature, t_{in}, at the intake of engine JMS 420 GS-N.LC at the loads $P_{el,ISO}/P_{el,ISO}$ = 0.6-1.0

As fig. 7 shows, an increase in air temperature at the intake of engine by 1 °C causes increasing the specific mass fuel consumption be by about 0.25 g/kWh.

Proceeding from reducing the specific mass fuel consumption be due to lowering the air temperature tin at the intake of engine, fig. 7, a concept of deep cooling the intake air lower than in traditional cooling system by chilled water from ACh with temperature of about 12 °C, fig. 2, generally used for technological duties, is proposed. This can be performed by addition cooling a chilled water from ACh down 5-7 °C to feed the air cooler at the intake of engine with application of ECh, fig. 8.

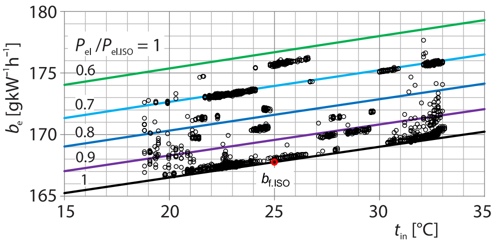


Figure 7. The values of specific mass fuel consumption, b_e, in dependence on the air temperature, t_{in}, at the intake of engine JMS 420 GS-N.LC at the loads $P_{el,ISO}/P_{el,ISO}$ = 0.6-1.0

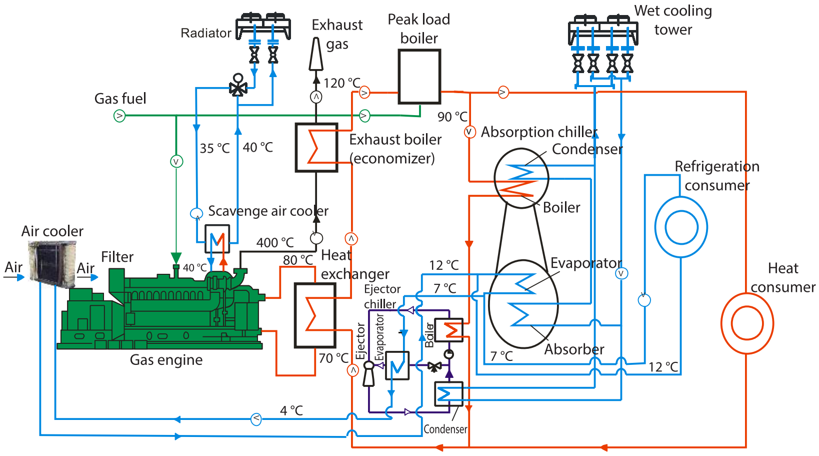


Figure 8. A proposed system for deep cooling a gas engine intake air by a chilled water from ACh additionally subcooled in ECh

As another version, a two-stage intake air cooler can be applied with precooling the ambient air to about 20 °C by chilled water from ACh in the first stage and subsequent deep cooling the air to the temperatures 7-10 °C in the second stage of the intake air cooler by using a refrigerant as a coolant.

Such deep cooling the air at the intake of engine provides its temperature drop of 15-20 °C resulting in specific mass fuel consumption reduction of about 2-3 g/kWh.

Conclusions

The fuel efficiency of gas engines is effected by the temperature of air at the TC suction. The data on dependence of fuel consumption and engine electric power on the intake air temperature were monitored for Jenbacher gas engine JMS 420 GS-N.LC to evaluate its influence.

The method for treating the monitoring data on fuel consumption depending on the air temperatures at the engine intake with regard to the influence of changes in engine loads was applied. It uses correlations from the generalized methodology presented in *ISO 3046-1:2002*

Reciprocating Internal Combustion Engines – Performance [39] with correction of the coefficients in calculation correlations on the base of monitoring data of gas engines JMS 420 GS-N.LC operating in a concrete IES.

The method is focused to determine the dependence of specific (volume or mass) fuel gas consumption on the engine intake air temperature to estimate the efficiency of engine intake air cooling at varying loading and to reveal the reserves to enhance the efficiency of traditional cooling system by ACh with chilled water generally used for technological duties.

Issuing from a reduction of the specific fuel consumption due to decreasing air temperature at the intake of engine a concept of deep cooling the intake air lower than traditional cooling by chilled water from ACh with temperature of about 12 °C generally used for technological duties, is proposed. It can be realized in two ways: by addition cooling a chilled water from absorption chiller to about 5-7 °C for feeding engine intake air cooler or by two-stage cooling with precooling ambient air by chilled water from ACh in the first stage and subsequent deep cooling air to the temperatures 7-10 °C in the second stage of intake air cooler by using a refrigerant as a coolant.

In both cases the ECh could be applied as the most simple in design and enabling addition decrease in intake air temperature by about 15-20 °C resulting in specific mass fuel consumption reduction of about 2-3 g/kWh. The corresponding scheme of engine intake air cooling system is proposed.

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