THE EVALUATION OF THE CHARACTERISTIC INJECTION TIMES OF A MULTIPLE FUEL DOSE

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Abstract

During research works on Common Rail injection systems it was found that there were differences between the set values of the injector opening times, the values of the opening times realized by the engine controller and the actual times of the injector needle lift. It is important to learn about the relation between the above-mentioned values, as there are significant time shifts between the start of the injector control impulse and actual start of the injection. Similar phenomena may be observed upon completion of an injection, where decay of the control signal is not tantamount to the settlement of the needle in the seat. This work aims at a determination of the scope, value and direction of the changes that the characteristic injection times are subject to depending on the injection time set, fuel dose and fuel pressure. Measurements the characteristic injection parameters were made in three basic groups differing in the set sequences of injection times and injection pressures. The knowledge of the characteristic injection times enables correct designs of the control algorithms for the operation of compression-ignition engines and it also enables a precise control of the fuel dose volume in the entire period of engine use. This is proved by development works related to ultra-high pressure common rail system and conducted by one of the leading manufacturers of engine fuel systems.

Keywords: *Diesel engine, Common Rail injection system, injection time, injection start delay time, injection end delay time*

1. Introduction

Contemporary, modern Diesel engines should be equipped in ultra high pressure injection systems to meet technical requirements in standards [3, 5, 8, 9]. Their injectors required to very short delay between the electric start of triggering and start needle lift [6, 7]. During research works on Common Rail injection systems it was found that there were differences between the set values of the injector opening times, the values of the opening times realized by the engine controller and the actual times of the injector needle lift. Moreover, some differences were found between the above-mentioned values and the injection times calculated based on the injection courses. It is important to learn about the relation between the above-mentioned values, as there are significant time shifts between the start of the injector control impulse and actual start of the injection. Similar phenomena may be observed upon completion of an injection, where decay of the control signal is not tantamount to the settlement of the needle in the seat. The time shift values are comparable to the values of the set impulses.

The knowledge of the shift values and their relation to the pressure of fuel in the accumulator or a method of division of a fuel dose into parts is significant for designing and modification of engine control algorithms. It may also help model an operating cycle of a compression-ignition engine.

2. The scope of the analysis

In electronically controlled common rail systems, the volume of the fuel dose injected is determined by a lot of factors. They include both structural parameters of particular elements of the system as well as values of the control parameters. Out of the control parameters, most important include the fuel pressure in the accumulator, the injector opening time and the method of fuel dose division. During operation of the system they enable the change of the volume of fuel fed and acquire various forms of injection course. They also influence the quality of atomization through a change of injection timing (angle) of the set fuel volume.

For the assumed pressure value in the accumulator and constant values of the injector throughput, the injection times constitute the value directly determining the volume of a fed dose. In the case of a fuel system built on the engine, the times selected by the designer are stored in the control module and used in accordance with the actual values of the engine speed and engine load. The Feeding of a set of time sequence (set injection time) to the injector solenoids causes the needle to lift. However, it is not lifted immediately. A period of time has to elapse, after which the needle will start to lift, as a result of which fuel will flow from the nozzle. This period is referred to as delay of the start of the injection. Similarly, the time from the completion of the feeding of an electrical signal control the injector until the completion of the fuel flow is referred to as delay of the injection end. However, the time from th commencement of the fuel flow at the beginning of the first fuel dose feed until the completion of the last part is referred to as the needle lift time. The above-mentioned and defined values, i.e. delay of the injection start and end and needle lift time are referred to as characteristic injection times.

This work aims at a determination of the scope, value and direction of the changes that the characteristic injection times are subject to depending on the injection time set, fuel dose and fuel pressure.

3. Methodology of measurements of the injection times

Values of the considered volumes were determined based on the testing of the common rail system as conducted in the sampling stand. During the measurements one of the injectors was placed in the chamber of the electronically controlled device for the measurement of the injection course (injection dose indicator), in which GU-21D a piezo quartz fuel pressure sensor manufactured by AVL was also embedded. The start of the fuel feed by the injector caused an increase in the pressure in the chamber as recorded in the form of changes of the voltage signal generated by the sensor. This enabled a measurement of the needle lift time.

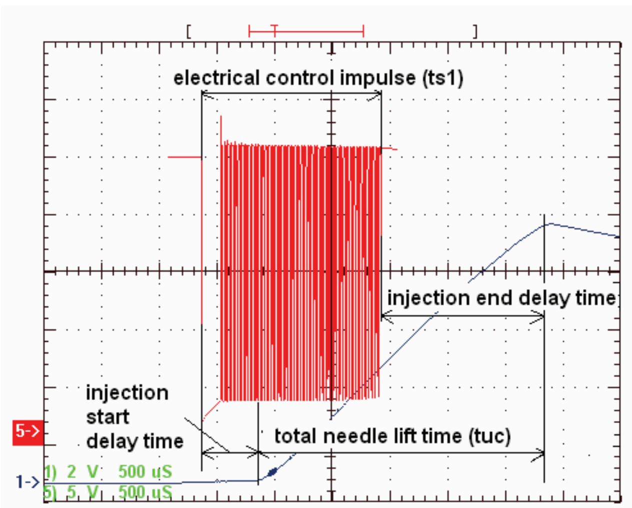

Fig. 1. Measured courses: injector control course (red line) and pressure in the indicator chamber (blue line) with characteristic injection times marked

Characteristic injection times were determined by analyzing the relation between the set injection times and the needle lift time. The set times were determined by measuring of the injector control voltage courses. The courses generated by the laboratory power system controller were measured at the outlet of the device with the use of Tektronix TDS-3014 digital oscilloscope (the red line in Fig. 1). The lift times were measured with the use of the same oscilloscope simultaneously with the control courses through the other channel of the device (the blue line in Fig. 1).

The averaged courses of 128 consecutive operating cycles were recorded in a form of files. They constituted a basis for the analyses contained in this study.

Fig. 1 presents examples of the measured courses, which constituted the basis for the analysis of an electrical impulse control a single dose injection (ts1) and the voltage signal of the pressure changes in the indicator chamber resulting from the flow of the fuel from the nozzle. The analyzed characteristic injection times were also marked.

4. Plans of the research

The fuel feed times for the fuel delivered by the injector depends on the control values adopted and, most of all, on the set injection times and the pressure in the accumulator. Therefore, considerations were made for various configurations of multiple doses with different time values and injection dwell times.

Tab. 1. The plan of the testing of the injection parameters

measured case No.	set injection times [μs]	total of set injection times [μs]	pressure in the rail [bar]
1	262_377_464	**1103**	305
2	262_377_464	**1103**	406
3	262_377_464	**1103**	500
4	262_377_464	**1103**	608
5	262_377_464	**1103**	692
6	262_377_262_377_1554	**2832**	632
7	262_377_1554	**2193**	716
8	1554	**1554**	824
9	262_377_262_567_451_1067_362_691_413	**4452**	379
10	262_377_262_567_451_1067_362_691_413	**4452**	452
11	262_377_262_567_451_1067_362_691_413	**4452**	562
12	262_377_262_567_451_1067_362_691_413	**4452**	648
13	262_377_262_567_451_1067_362_691_413	**4452**	764

Measurements were made in three basic groups differing in the set sequences of injection times:

- group 1 – the measurement of fuel doses in the sampling stand and the measurement of the injection course with the use of an indicator, including very small doses (for the division of a dose into two parts – the first part - 262 μs, dwell time 377 μs, the other part - 464 μs) for gradual increase of pressure in the accumulator (measurement points - 1, 2, 3, 4 and 5). A use of small values of set times and low injection pressures were assumed;
- group 2 – the measurement of fuel doses in the sampling stand and the measurement of the injection course with the use of an indicator (for division into three, two and one part). In light of the sensor strength maximum constant pressure in the indicator chamber was maintained as well as constant values of the collective injection doses measured in the stand (measurement points - 6, 7, 8). The measurement points were entered in Tab. 1 according to the incremental values of the pressure in the accumulator; the pressure was the resulting value;
- group 3 – the measurement of the fuel doses in the sampling stand and the measurement of the injection course with the use of an indicator (for the division into five parts – the first part - 262 μs, dwell time of 377 μs, the second part - 262 μs, dwell time of 567 μs, the third part - 451 μs, dwell time of 1067 μs, the fourth part - 362 μs, dwell time of 691 μs, the fifth part - 413 μs). The incremental values of the pressure in the accumulator were set with the use of the normal

operating range of the system until the attainment of the maximum admissible value in the indicator chamber (measurement points – 10-14). Multiple doses were introduced for the purposes of the evaluation of the relation between the dwell times and the individual doses.

5. Characteristic injection times

The simultaneous recording of the values of the pressure increment in the indicator and the signals control the injector operation enables determining the characteristic injection times as discussed at the beginning of this study, namely the delay of the start of the injection and its end (Fig. 1). The obtained values were compared for each of the three tested groups. As the analyzed values have a direct impact upon the total needle lift time, this value was also considered.

The characteristic injection times for two- and five-part doses depending on the volume of the fuel fed were presented in a common chart (Fig. 2).

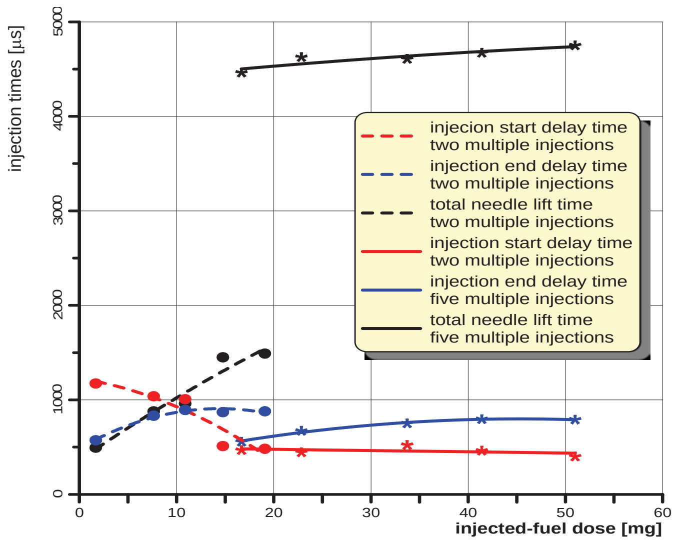

Fig. 2. The delay of the injection start and end depending on fuel dose

The delay of the start of the injection, understood as the time between the beginning of the control impulse and the beginning of an increase in the pressure in the indicator chamber (red line), decreases with an increase in the injection dose. In the case of feeding a two-part dose, a significant change can be observed in the considered range as the change reaches 60% of the initial value. For five-part doses, the delay of the start of the injection is less diversified and it changes by 23% in the considered range.

The delay of the injection end (i.e. time measured between the decay of the control signal and the completion of an increase in the pressure in the indicator) assumes very similar values for the first and third measurement group. In the considered ranges, an increase in the volume of the fuel fed is accompanied by an approximately 30% increase of the considered value (blue lines).

Very similar courses of the discussed values are obtained depending on the pressure of the fuel in the accumulator due to constant values of the set injection times.

A decrease in the delay time of the start of the injection results from the principle of operation of the Common Rail system. Higher pressure values cause the needle to lift with greater velocity than for lower pressures, which results in decreased delays of the start of the injection.

The process of injector closing at high pressure is, in turn, impeded by the fuel remaining under the needle. As the impulse is sent to the cut-off valve for the fuel flowing from the injector control chamber, the pressure increases in the chamber. However, the holes in the injector control chamber have a lesser flow surface than the nozzle, are characterized by choking and, therefore, the pressure in the control chamber increases mores slowly and the movements of the control piston and the needle are also slower. As a result, the delay of the injection end increases.

Hydraulic phenomena are also accompanied by electrical phenomena taking place in the injector control valve. Fig. 3 presents an example of voltage changes (red line) and valve control current (blue line) recorded for the division of the dose into five parts. The valve includes a coil and an armature drawn by the coil. The coil constitutes a classic two-terminal element, i.e. an element characterized not only by resistance, but by inductiveness as well. It is the inductiveness that causes the slower increase and a relatively long decay of the valve control current. In the controller built for the purposes of the operation the control of the needle lift, i.e. an increase in the coil activating current and, thus, the control of the electromagnetic stream generating the force that brakes the armature has a very quick course. The period of time from the beginning of the signal feed until the attainment of the maximum intensity of control current is 140 μs. It is different in the case of the control of the injection end. Here, the time is ten times longer, which has an influence upon an increase in the injection delay values.

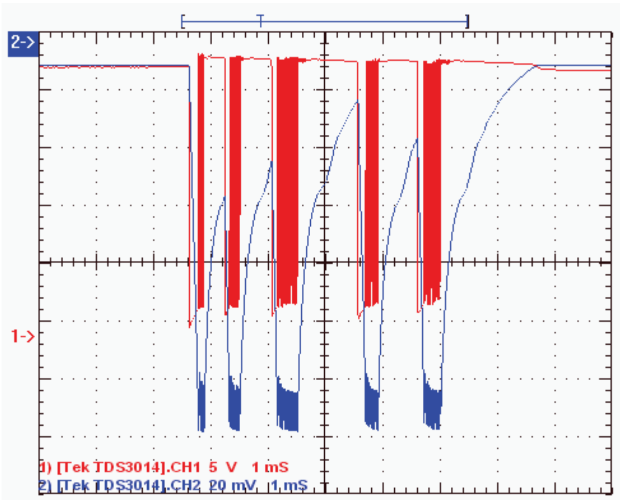

Fig. 3. Courses of injector control voltage and current for division of the dose into five parts

Despite the fact that the set injection times in the first and third measurement group do not change, the total needle lift times as read from the pressure courses in the indicator chamber (Fig. 2, black lines) increase with an increase in the injection dose. The total values of the set times for the first group are nearly four times lower than for the third group and total lift times grow faster as a result of a feed of two-part doses. The average time increment is 57.2 μs/mg of fuel (2.57 μs/bar). For five-part doses, the lift times are much slower and amount to 8.4 μs/mg of fuel on average (0.75 μs/bar). Such significant differences result from the adopted research plan assuming a setting of relatively short times for the first measurement group and low injection pressures for some points. This way, small doses were obtained, which, despite setting of the division into two parts, remained mostly unrealized as divided due to much lower pressure. It should be noted that the absolute values of the delay of the start of the injection as read for the first group of measurements were more than twice as high as the third group. An increase in pressure causes a decrease in the delay of the start of the injection and an extension of the injection end, i.e. the extension of the total needle lift time. The relatively long time taken by the needle to settle in the seat, resulting from the course of the control current has a larger percentage share in the total lift times for two-part doses than it is for long lift times divided into five parts. Therefore, the total lift times increase quickly for two-part doses.

There is another reason for an increase in the time values of the delay of the injection end and the total lift times - spontaneous magnetism (residual magnetism) of the injector valve armature remaining in the armature at zero magnetic field upon switching off the control signal. The residue is increased with an increase in the last part of the set injection time. In order to determine the influence, additional measurements were made. In order to avoid influence of additional factors upon the values obtained, the measurements were made only for one-part doses. For the constant value of the pressure in the accumulator (660 bar), times of 1000, 1200 and 1500 μs were set. The results are presented graphically in Fig. 4. The figure depicts a visible increase of the delay of the injection end and the needle lift times in relation to the set values. This proves a significant influence of the spontaneous magnetism upon the values of the delay of the injection end.

The delay of the injection end is at the unchanged level because the constant value of the fuel pressure during the measurements is maintained.

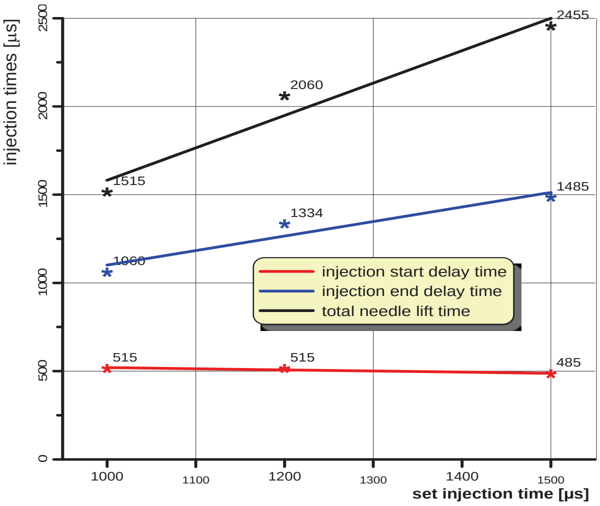

Fig. 4. Total needle lift times, delay of the start and end of the one-part injection depending on the set injection time

Similar measurements for one-part dose were made for the purposes of evaluation of the influence of the pressure in the accumulator upon the characteristic injection times. An increasing trend was observed in relation to the delay of the injection end for the set constant injection time and the increasing values of the pressure in the accumulator. During the tests conducted in the sampling stand, the injection time of 1000 μs was set for three pressure values (Fig. 5). The previous observations were confirmed and, at the same time, it was found that a decrease in the delay of start of the injection has an influence upon an increase in the total needle lift time.

The influence of the interval between dose parts upon the characteristic injection times also had to be evaluated. Therefore, additional measurements were made for two-part injection dose (262 μs_dwell time 464 μs) for constant values of the fuel pressure in the accumulator – approximately 700 bar (Fig. 6).

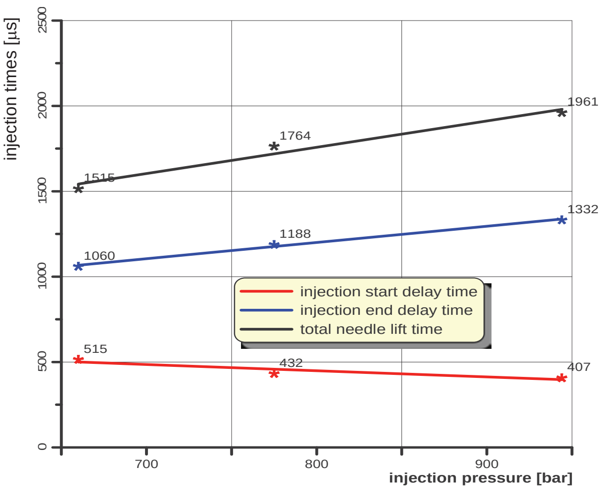

Fig. 5. Total needle lift times, delay of the start and end of the one-part injection depending on the injection pressure

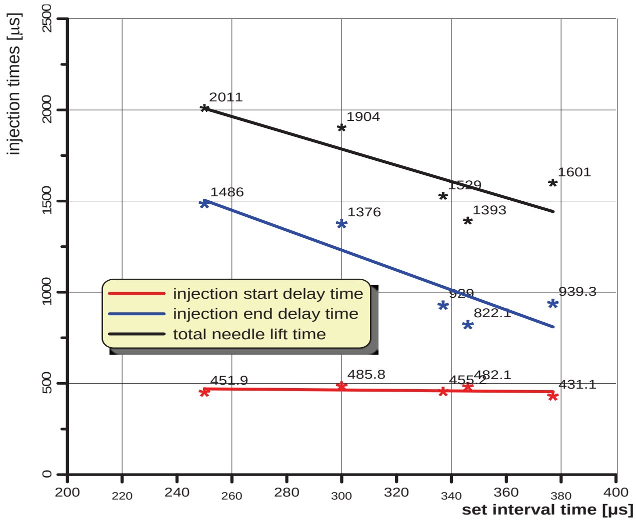

Fig. 6. Total needle lift times, delay of the start and end of the injection for the two-part dose depending on the set interval time

An increase in the dwell time is accompanied by a visible decrease of the delay of the injection end and the total needle lifts time, whereas the delay of the start of the injection remains unchanged. The course of the delay of the start of the injection can be relatively simply explained, because for each given type of injector it depends on the pressure in the control chamber (accumulator) and it was maintained on the constant level in the discussed case. The course of the changes of the delay of the injection end in turn considerably depends on the time of activation of the injector coil. For the discussed measurements, the dwell time of 250 μs was set. This value did not cause the needle to lower, first of all, due to a long time of decay of the current intensity in the coil of the control valve upon feeding of the first part of the dose. In fact, the coil was fed for the period of time that equalled the total activation and dwell times, i.e. approximately 1000 μs. Therefore, for the initial points, considerable values of the delay of the injection ends were recorded as compared to the values obtained for longer one-part times. The delays decrease with time, as a longer dwell time enables a decrease in the control current intensity to such a considerable extent that the momentary activation of the valve is decreased as accompanied by a decrease in the magnetic stream in the coil. As a result, for the dwell time of approximately 370 μs, it was found that the doses were divided into two parts. However, it should be noted that the visible division into parts depends not only on the dwell time duration, but also on the fuel pressure – with an increase in the fuel pressure it is more difficult to obtain a division of the dose. This relationship should be taken into account when planning injection maps.

The described phenomena also affect a decrease in the total needle lift time.

Upon completion of the above-mentioned additional measurements, the characteristic injection times for the other group of measurements were evaluated. The results for this group were obtained for a constant dose and different times and fuel pressures set in the accumulator (Fig. 7). The delay of the injection end decreases with an increase in pressure. This course of delay is affected by two factors. The first factor, which, in the case of the second group of measurements, has a weaker influence, involves increasing the injection pressure, which caused an increase in the delay in all previous discussions (except for the dwell time). However, the influence of this factor was dominated by the other factor with stronger influence - the set injection time. In the discussed measured group, the set injection times are decreased with the pressure increase in order to obtain the same volume of the injected fuel. Owing to a decrease in the injection times, the magnetism of the valve elements is decreased and, at the same time, it is possible to decrease the delay times of the injection end. The adopted dwell times do not ensure a total decay of the control current intensity in the valve and, at the same time, the coil is activated for the entire period of duration of the control sequence, although, during the dwell times, it is activated with the use of lower intensity current.

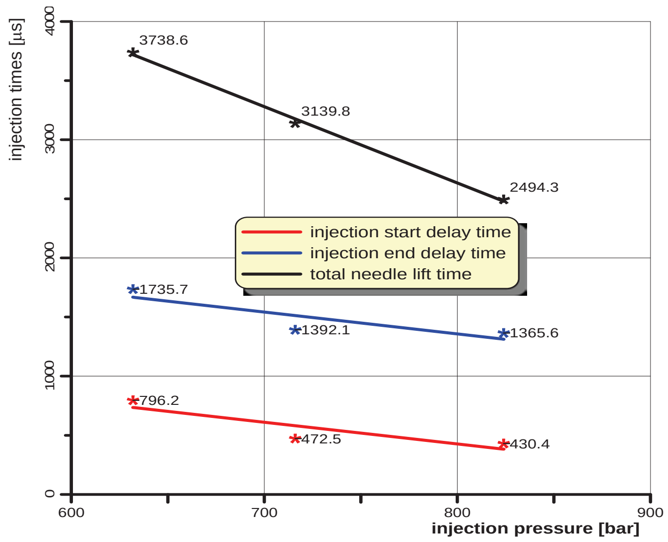

Fig. 7. Total needle lift times, delay of the start and end of the injection for the two-part dose depending on pressure in the accumulator for the second group of measurements

Moreover, the injection times set for this group have one common characteristic - their last part was relatively longer (1554 µs). This could be the reason for obtaining of higher values of the delay of the injection end as compared to the values obtained for points with similar pressure value.

The course of the delay of the start of the injection does not differ from the courses of the other groups and it decreases with an increase in pressure. The total needle lift times decrease, which results, first of all, from the decreasing set injection times and the previously mentioned factors connected with the changes of the delay of the injection end.

6. Conclusions

Despite constant values of the set injection times, the total needle lift times increase with an increase in the fuel pressure. For lower times set this is a large increment. It is due to the fact that as a result of the influence of the pressure, the delay of the start of the injection decreases and the delay of the injection end increases. The delay times may be identified with the speed of the needle movement, although it is not a precise note, as the times constitute values depending on the times of the movement of the valve, the control piston and the very needle as well as the characteristic sizes of those elements.

For the maintenance of a constant fuel pressure and an increase in the set injection times, unchanged values of the delay of the start of the injection and an increase in the delay of the injection end can be observed. Setting higher time values causes an increase in the spontaneous magnetism of the valve, which is translated into an increase in the needle lift times.

An increase in the set interval times and simultaneous maintenance of a constant fuel pressure leads to obtaining of unchanged values of the delay of the start of the injection and a decrease in the delay of the injection end. As a result, the total needle lift time decreases, which are caused by a decrease in the intensity of the control current and, at the same time, magnetic stream in the coil and the actual realization of the set dwell time. Therefore, the injected fuel doses were decreased.

The knowledge of the characteristic injection times enables correct designs of the control algorithms for the operation of compression-ignition engines and it also enables a precise control of the fuel dose volume in the entire period of engine use. This is proved by development works related to ultra-high pressure common rail system and conducted by one of the leading manufacturers of engine fuel systems [9].

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