TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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A COMPARISON OF IGNITION CHARACTERISTICS OF DIESEL FUELS AS DETERMINED IN ENGINES AND IN A CONSTANT-VOLUME BOMB

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SUMMARY

Ignition-lag data have been obtained for seven fuels injected into heated, compressed air under conditions simulating those in a compression-ignition engine. The results of the bomb tests have been compared with similar engine data, and the differences between the two sets of results are explained in terms of the response of each fuel to variations in air density and temperature.

INTRODUCTION

Earlier tests with the N.A.C.A. high-temperature bomb (reference 1) have shown that the ignition lag at the highest bomb temperature is roughly twice that for the same fuel in an N.A.C.A. high-speed Diesel engine having a comparable air density at top center. The minimum engine ignition lags reported by Schweitzer (reference 2) are in substantial agreement with those obtained with the bomb.

It has been reported (reference 3) that the C.F.R. engine fuel ratings are in substantially the same order when either the critical-compression-ratio (C.C.R.) or the ignition-delay method is used. The fact that the C.C.R. method involves longer ignition lags than the delay method indicates that the bomb would also give comparable ratings provided that the greater air turbulence in the engine was not an influential factor. On this basis, tests were made in the bomb with fuels of different ignition qualities, or different cetane numbers, to determine the limitations of this apparatus for rating fuels. The test conditions included bomb temperatures of 870° and 1,155° F. and air densities of 0.59, 0.89, and 1.18 pounds per cubic foot.

The engine data with which these results are compared were obtained with an N.A.C.A. displacer-type compression-ignition engine at 2,000 r.p.m. and a compression ratio of 14.5 (reference 4).

FUELS TESTED

Seven fuels have been tested in the bomb, three of which were obtained by adding an ignition accelerator to a single base fuel designated L_1 Diesel in the table and the figures. Ethyl nitrate was used for two of these fuels and a commercial Diesel dope for the third fuel. The four other fuels used in the bomb were selected from among eight fuels tested by this laboratory in a compression-ignition engine. The properties of the eight previously tested fuels are listed in table I; the properties of the three fuels with added ignition accelerator are not available. With the exception of the N.A.C.A. engine data (the ignition lags, the maximum pressures, and the maximum rates of pressure rise), all the data in this table were furnished through the courtesy of the United States Naval Engineering Experiment Station, Annapolis, Md. The cetane ratings were obtained by the procedure recommended in reference 3, using the constant ignition-delay method with a modified magnetic pick-up.

RESULTS AND DISCUSSION

The ignition lags obtained both in the bomb and in the N.A.C.A. engines depend upon a slight increment of pressure to denote ignition; whereas the cetane numbers cited depend upon an ignition denoted by the attainment of a certain rate of pressure rise after ignition. The two methods can give comparable results only if the rate of pressure rise and the smallest detectable pressure increment are determined by the true ignition lag and are not influenced by the viscosity, the surface tension, the distillation characteristics, or other physical properties of the fuel. The bomb records obtained in this study would be ideally suited to test the validity of this point were it not for the fact that their pressure and time scales are too condensed to permit an accurate determination of the initial rates of pressure rise. That the lags and the cetane numbers for the usual range of

Diesel fuels are in general agreement is indicated by the small deviation in cetane equivalent from one ignition-indication method to another (references 3, 5, and 6).

The records reproduced in figure 1 are typical and show the effect of ignition lag on combustion. Both records were taken under identical conditions except for gas temperature. It is evident that, in spite of a much longer ignition lag, the low-temperature record indicates complete combustion in about half the time required at the higher temperature. This result is believed to be good evidence that slow burning in a compression-ignition engine is not entirely a matter of inadequate mixing of fuel and air. Such mixing should have been just as satisfactory, in a given time, at one bomb temperature as another, irrespective of whether or not combustion was taking place. If anything, the earlier combustion at the higher bomb temperature should have increased the rate of mixing and therefore the rate of pressure rise because of the induced convection currents. The high rate of pressure rise, in addition to the vibrations evident in the low-temperature record, is an excellent reason why long ignition lags are not permissible in an engine.

The ignition lags for each fuel and test condition shown in figure 2 are averages of the most consistent values obtained for several fuel-air ratios ranging from 0.0400 to 0.0167. In general, the ignition lags for all fuel-air ratios were reproduceable and in agreement within 0.0003 or 0.0004 second or better. This variation in the ignition lags is too great for checking to within one or two cetane numbers, as may be seen from figure 2 and from the corresponding cetane values in table I. In fact, this variation would have to be reduced by a factor of at least 10 in order to check to within one cetane number, as is now possible with the C.F.R. Diesel and the various ignition indicators that average a great many cycles. Further improvements in the bomb instrumentation and operation should considerably reduce the existing variation in lag. The optical indicator (reference 1) used in the bomb tests was not completely satisfactory either optically or mechanically at the high temperatures employed in these tests.

Figure 2 shows the same tendency for the ignition lags of all fuels to converge with increasing air densities and temperatures as they do with a decreasing injection advance angle (reference 7). When ignition occurs before top center, decreasing the injection advance angle is equivalent to using a constant advance angle and increasing the compression ratio which, in turn, is equivalent to increasing the air temperature and density in the bomb. Michailova and Neumann (reference 8), as well as Schweitzer (reference 2), have also noted this tendency for all fuels to approach a limiting ignition lag.

In addition to the relative ignition-lag order for fuels under specified engine conditions, the change in this order with decrease in compression density and temperature may become of interest in the rating of fuels for aircraft Diesel engines required to operate above the critical altitude of the engine. This change in the bomb rating order with air density is illustrated by the curves that cross in figure 2. A similar change with temperature is shown in figure 3 by the divergence of the Marine Diesel fuels from the trends exhibited by the other fuels.

No particular difficulty in obtaining suitable fuels for aircraft Diesel engines is expected, however, for several reasons: (a) Some margin in ignition quality will always be necessary to secure good starting characteristics; (b) sufficient margin in ignition quality will not greatly increase the initial fuel cost; (c) the increase in ignition lag with altitude can be wholly or partly compensated by an increase in injection advance angle (reference 9), the rate of pressure rise being the only limiting factor; and (d) the possible variation in lag becomes smaller the greater the air temperature and density or the higher the cetane equivalent of the fuel, as is shown by figure 2. For these reasons a change in rating order will not be serious, particularly if the fuels prove satisfactory under sea-level conditions and the change in rating order occurs at a relatively low density or temperature. Such a change is evident in figure 2 for the L_1 fuel plus 5 percent ethyl nitrate and the L_1 fuel plus 2 percent commercial dope at 807° F. The type of change shown by the No. 3 furnace oil and the Marine Diesel fuel at the same temperature, however, might be objectionable. In any case, if the fuel-ignition requirements warrant such a procedure, the fuel ratings can be determined under simulated altitude conditions either in a suitable bomb or in an engine.

In figure 3, the ignition lags of several fuels in an N.A.C.A. engine and in the bomb at two temperatures are shown plotted against their respective cetane numbers.

All the bomb data correspond to an air density of 0.89 pound per square inch, this value being approximately the maximum density in the engine.

The ignition lags for the Marine Diesel fuel in the bomb were much too great to be consistent with the lags for the other fuels. This irregularity became smaller the higher the temperature and, of course, must disappear altogether in the C.F.R. Diesel since the rating method stipulates a constant ignition lag for all fuels. Dotted curves have been drawn between the points for the other fuels on the assumption that these curves most nearly approximate the curves that would be obtained with mixtures of the reference materials - cetane and alpha methylnaphthalene. Both curves show the same tendency to flatten out toward the right of the figure, as they must in order to avoid crossing in the region of fuels of high ignition quality.

In the case of the N.A.C.A. engine data, the Marine Diesel fuel is again slightly irregular but the deviation is in the opposite sense from that observed in the bomb. This deviation, though small, is believed to be greater than the experimental error in view of the consistency of the other data. This result indicates that the effective temperatures prevailing in the N.A.C.A. engine are somewhat higher than those in the C.F.R. engine. The engine and the bomb data also show that the lower the temperature, the greater is the variation in ignition lag per cetane number, particularly in the lower cetane region. Other conditions being equal, therefore, the higher the effective air temperature and density in an engine, the less sensitive that engine should be to the ignition quality of the fuel.

CONCLUSIONS

1. The rating order for certain Diesel fuels, as indicated by the ignition lags in the bomb, may change with variations in either air temperature or density.

2. Usually, the lower the air temperature and density at which ignition takes place, the greater is the spread between the ignition lags of two fuels.

3. With the exception of the Marine Diesel fuel, the

rating order obtained with the bomb was the same as that with an engine.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 28, 1939.

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TABLE I(a) - PROPERTIES OF DIESEL FUELS

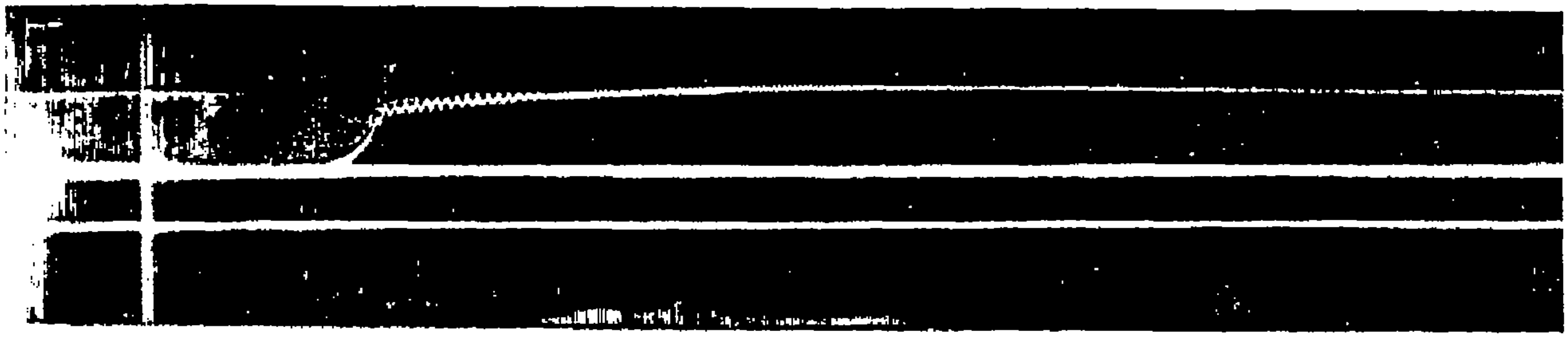
Fuels	Ignition lag, N.A.C.A. engine (sec.)	Cetane number	Maximum cylinder pressure, balance diaphragm (lb./sq. in.)	Maximum rate of pressure rise (lb./sq. in./sec.)	Specific gravity, 60/60	Flash point, closed cup (°F.)
No. 3 furnace oil[a]	0.00096	29.9	1050	840,000	0.877	162
75 percent L_1 and 25 percent 87 octane gasoline	.00083	42.4	875	440,000	.799	below 80
No. 3 furnace oil and 1 percent ethyl nitrate	.00083	47.7	960	650,000	.875	125
Navy submarine 7-0-2C[a]	.00079	49.2	930	600,000	.852	188
Marine Diesel[a]	.00067	58.0	930	480,000	.843	182
Navy aircraft M306	.00075	59.9	935	610,000	-	-
L_1 Diesel[a]	.00071	62.5	920	520,000	.833	236
L_1 and 1 percent isoamyl nitrate	.00054	88.	950	280,000	.834	145

Fuels	Cloud point (°F.)	Pour point (°F.)	Saybolt universal viscosity 32°F. (sec.)	Saybolt universal viscosity 100°F. (sec.)	Carbon residue (percent)	Gross heat value (B.t.u./lb.)	Aniline point (°F.)	Parrafins by volume (percent)	Unsaturates by volume (percent)	Naphthenes by volume (percent)	Aromatics by volume (percent)
No. 3 furnace oil[a]	Indistinct	-65	58	38	0.022	19,315	126	62.9	4.1	19.1	13.9
75 percent L_1 and 25 percent 87 octane gasoline	8	10	42	35	.039	19,775	171	76.7	1.5	17.5	4.3
No. 3 furnace oil and 1 percent ethyl nitrate	-10	-25	57	38	.126	19,257	130	63.5	2.6	16.5	17.4
Navy submarine 7-0-2C[a]	12	10	65	39	.025	19,660	157	67.3	6.9	15.8	10.4
Marine Diesel[a]	14	15	61	38	.017	19,578	161	70.9	2.3	17.2	9.6
Navy aircraft M306	-	-	-	-	-	-	-	-	-	-	-
L_1 Diesel[a]	28	25	93	44	.010	20,042	186	-	-	-	-
L_1 and 1 percent isoamyl nitrate	28	25	86	43	.062	19,696	183	75.3	.4	18.2	6.1

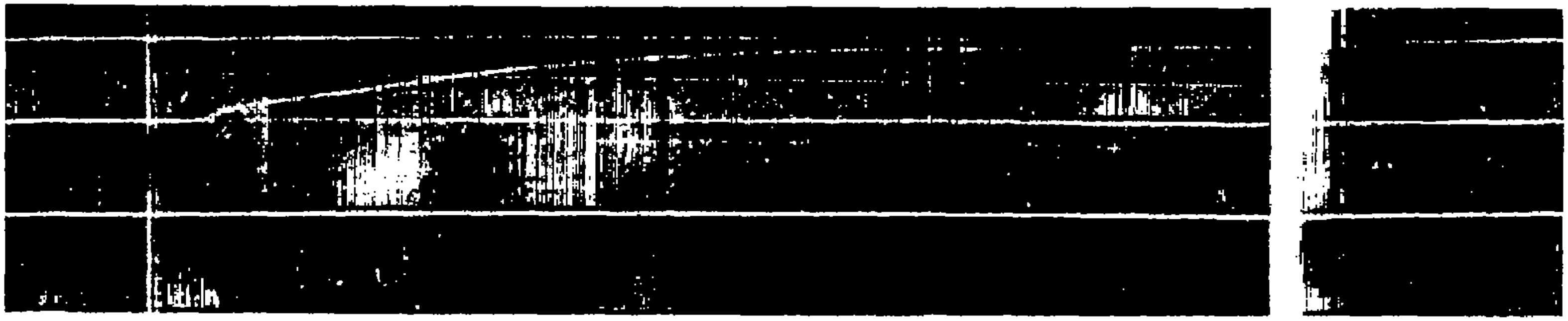
TABLE I(b) - DISTILLATION CHARACTERISTICS OF DIESEL FUELS

Fuels	First drop (°F.)	5cc. (°F.)	10cc. (°F.)	20cc. (°F.)	30cc. (°F.)	40cc. (°F.)	50cc. (°F.)	60cc. (°F.)	70cc. (°F.)	80cc. (°F.)	90cc. (°F.)	End point (°F.)	Recovered (percent)
No. 3 furnace oil[a]	375	424	438	456	470	484	497	512	527	547	581	640	98.7
75 percent L_1 and 25 percent 87 octane gasoline	135	169	182	224	474	550	560	570	580	594	617	658	97.8
No. 3 furnace oil and 1 percent ethyl nitrate	212	428	442	462	476	490	504	518	534	556	590	647	98.3
Navy submarine 7-0-2C[a]	421	461	475	492	508	521	533	545	558	574	600	661	98.7
Marine Diesel[a]	408	440	453	472	493	509	525	541	559	582	619	673	98.4
Navy aircraft M306	-	-	-	-	-	-	-	-	-	-	-	-	-
L_1 Diesel[a]	529	540	546	554	561	568	575	582	590	602	622	672	98.4
L_1 and 1 percent isoamyl nitrate	188	520	545	554	561	568	575	583	591	601	622	660	98.0

[a] Fuels tested in the bomb.



870° F. Bomb temperature



1,155° F. Bomb temperature

Figure 1.- Effect of ignition lag on combustion. L1 Diesel fuel plus 5 percent ethyl nitrate; air density, 1.18 pounds per cubic foot; fuel-air ratio, 0.033.

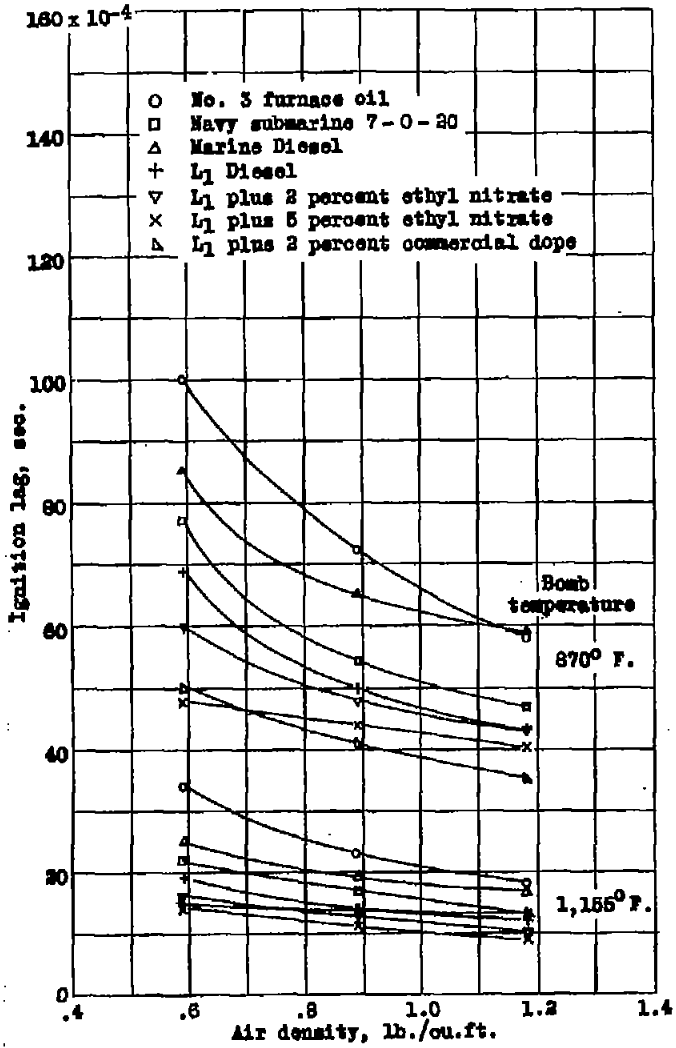


Figure 2.- Effect of air temperature and density on ignition lags in a bomb.

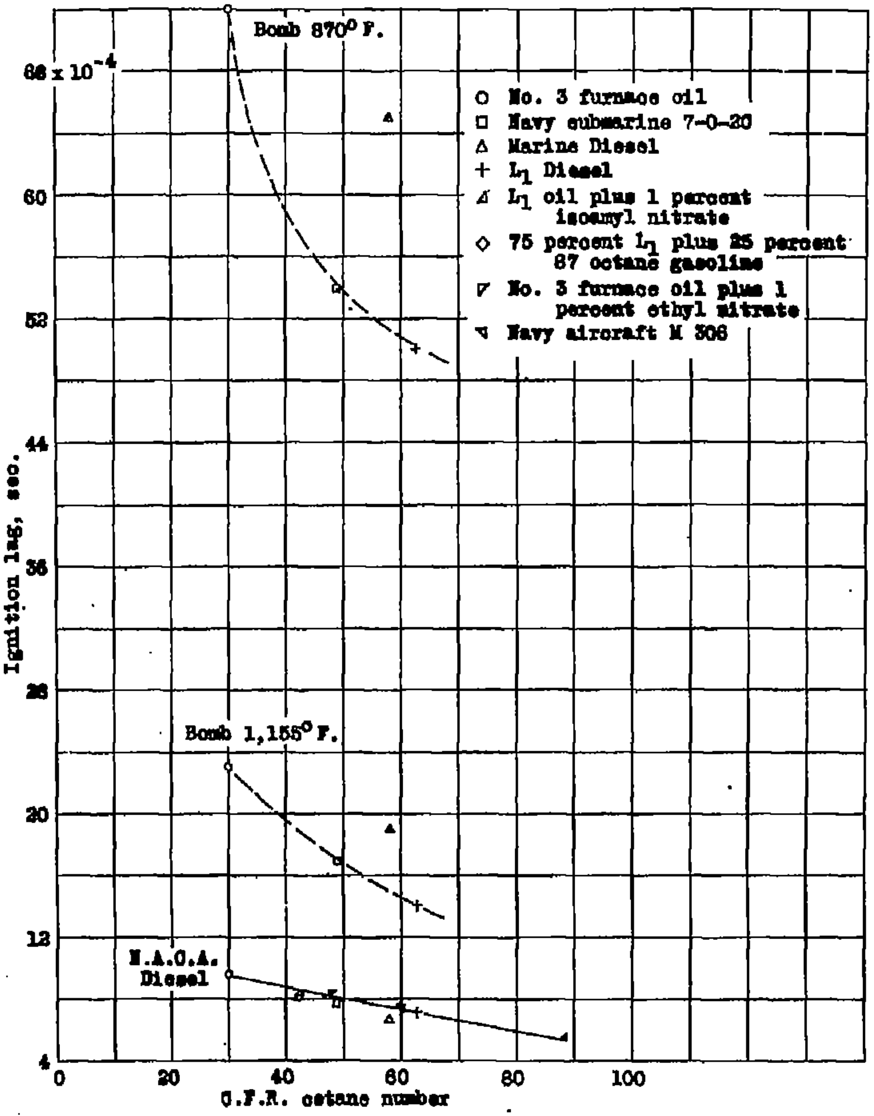


Figure 3.- Comparison of N.A.C.A. engine and bomb ignition lags.