NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3829

EFFECT OF PRESSURE ON THE SPONTANEOUS IGNITION TEMPERATURE OF LIQUID FUELS

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Washington
October 1956

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SUMMARY

Spontaneous ignition temperatures from 1 to 9 atmospheres were measured in air for n-heptane (straight-chain paraffin), isooctane (branched-chain paraffin), benzene (aromatic), and JP-4 and JP-5 fuels. A 125-cc Erlenmeyer flask was employed as the ignition chamber, and fuel was injected in a solid stream (no spray) into the flask enclosed in a bomb. Fuel charges were varied to obtain the lowest temperature at which ignition occurs. Time lags before ignition were measured at each pressure for all fuels.

All fuels that were tested showed a decrease in the spontaneous ignition temperature as the pressure was raised; the rate of decrease was greatest in the range of 1 to 3 atmospheres. The total decrease of the spontaneous ignition temperature over the pressure range considered was 276° C for benzene, 236° C for isooctane, 60° C for n-heptane and JP-4 fuel, and 41° C for JP-5 fuel.

The difference in the spontaneous ignition temperature of two fuels at 1 atmosphere becomes less at a higher pressure. For example, JP-4 and JP-5 fuels differ by 25° C at 1 atmosphere and by 8° C at 9 atmospheres.

Two jet fuels that were specified as JP-4 showed a constant difference of about 20° C in the spontaneous ignition temperature over the experimental pressure range. By percolation of the fuel samples through silica gel, the spontaneous ignition temperature of the fuel with the higher value was reduced by approximately 10° to 12° C.

From a limited number of ignition lag experiments with n-heptane, the lag was found to decrease with increasing pressure. Experiments were performed with three fuel charges, and ignition lags were measured at three pressures with each charge. Semilogarithmic plots of the time lag against the reciprocal of the absolute temperature gave lines showing

some curvature. Activation energies were calculated from the slope of these curves, and were found essentially invariant with variation of fuel charge and pressure. The average activation energy was approximately 21,000 calories per mole.

INTRODUCTION

The minimum temperature at which fuel-air systems will spontaneously ignite is an important factor in the safe handling of fuels in aircraft and elsewhere. These spontaneous ignition temperatures have been studied by many investigators in the past using a wide variety of techniques. The lowest ignition temperatures were obtained when liquid fuels were introduced into a heated container (ref. 1). A considerable amount of such data, taken at 1 atmosphere pressure, is available (refs. 2 to 4).

However, there are conditions in flight where fuel and air may come in contact with hot surfaces at pressures above 1 atmosphere. Relatively little is known about the minimum ignition temperature of practical fuels under these conditions. Ignition temperatures of liquid hydrocarbons above atmospheric pressure were measured in reference 3; in reference 5 premixed fuel-air mixtures were introduced into heated bombs. Ignition temperatures so measured are higher than those obtained by other techniques. In both references 3 and 5, increasing the pressure lowered the ignition temperatures. Reference 2 reports the same effect over a range of subatmospheric pressures.

In the present work, spontaneous ignition temperatures were determined in air at pressures from 1 to 9 atmospheres for three hydrocarbons (representing three basic types) and two jet engine fuels. A 125-cc. Erlenmeyer flask was used as the ignition chamber. The flask was enclosed in a cylindrical bomb. The fuels used were n-heptane (straight-chain type), 2,2,4-trimethylpentane (branched chain), benzene (aromatic), and JP-4 and JP-5 jet fuels. Where comparison is possible, the values reported herein at atmospheric pressure are compared with those of previous workers. A small number of ignition-lag experiments for n-heptane are presented for three fuel charges at three pressures. From semilogarithmic plots of ignition lag against the reciprocal of temperature 1/T, activation energies are computed for this fuel.

APPARATUS

Spontaneous ignition temperatures for five liquid fuels were determined at pressures above atmospheric with the apparatus shown in figure 1. The ignition chamber was a 125-cc Erlenmeyer Pyrex flask (except for experiments with benzene where a Vycor flask was used). At the base of the flask, a T-shaped glass tube was attached to supply thermocouple and sweep air inlets. A glass-fiber insulated heating mantle was employed as the heat source. The heating current was controlled with a variable transformer. The flask, fitted with the mantle, was placed inside a cylindrical cast-iron bomb which had a $10\frac{1}{2}$-inch inside diameter and an 18-inch depth. Two observation ports diametrically opposite were located in the bomb wall.

Near the base of the bomb, two thermocouples entered. One was attached to the heating mantle, and the other was placed inside the flask near the bottom. Preliminary work showed that temperature differences in the flask between the bottom and the neck were less than 3° C. Filtered service air was supplied to the bomb at two points through 1/4-inch copper tubing. A pressure gage with a scale graduated in units of 2 pounds per square inch was employed.

The fuel line entered the cylinder near the top. A 0.052-inch (I.D.) fuel delivery tube was placed about 1 inch above the flask mouth. In the removable cover of the bomb were the exhaust valve and the rupture disk. All connections through the bomb wall were made with pressure fittings capable of withstanding a pressure of more than 300 pounds per square inch.

The fuel-injection device was a Bosch pump equipped with three cylinders. With a single revolution of the pump crank, all cylinders were fired simultaneously. The pump was modified so that one, two, or all cylinders could be fired at will. In addition to varying the number of cylinders used, the position of the "rack" (a volume control found on all Bosch pumps) was varied and calibrated. Thus, the amount of fuel delivered by one or more cylinders at a single rack position was known. This gave wide diversity to the size of the fuel charge for a single revolution of the pump crank (i.e., 0.1 to 1.1 cc).

PROCEDURE

The spontaneous ignition temperatures reported here may be considered minimum for the particular apparatus employed. Minimum temperatures were ensured by injecting the fuel in a solid stream and by varying the amount injected. Injection of the fuel in a solid stream is important, since if the fuel is sprayed, a higher spontaneous ignition temperature is obtained (ref. 3).

The following procedure was employed to determine the spontaneous ignition temperatures. The flask was heated to the desired temperature and air was added to give the test pressure. After the addition of air, the temperature decreased slightly, and the system was allowed to regain the desired temperature. Then, simultaneously the fuel was injected and the timer started. On the appearance of a flame the timer was stopped and the elapsed time was taken as the ignition lag. No attempt was made to detect cool flames by darkening the room. Neither puffs of smoke nor sudden sharp increases of temperature alone were taken as an indication of ignition. Following each test where ignition occurred the flask was swept out with air, and the procedure was repeated at a lower temperature. If no ignition occurred (after 3 or 4 min), a test was made at the same temperature with a larger fuel charge. If no flame was observed after increasing the charge (usually by 0.1 cc or more), the temperature at which ignition was last observed was recorded as the spontaneous ignition temperature at the particular pressure. When the several ignition temperatures were completed for one fuel, the flask was thoroughly cleaned before beginning measurements with a new fuel.

The temperature difference between ignition and no ignition was not more than 3° to 5° C. For all the fuels reproducibility was within 5° C. Check points are shown on all the spontaneous ignition temperature - pressure plots.

The n-heptane and isooctane were obtained from a manufacturer who specified the purity as 99 mole percent or better. Redistilled nitration grade benzene with a comparable purity was employed in addition to JP-4 and JP-5 jet aviation fuels.

RESULTS AND DISCUSSION

Minimum spontaneous ignition temperatures obtained for five liquid fuels in air within the pressure range of 1 to 9 atmospheres are given in table I. The time lag before ignition is also included.

Effect of Pressure on Spontaneous Ignition Temperature

Plots of spontaneous ignition temperature against pressure are shown in figure 2 for all fuels tested.

n-Heptane. - For n-heptane (fig. 2(a)) the spontaneous ignition temperature decreases rapidly from 250° C at 1 atmosphere to 212° C at 2 atmospheres. Above 2 atmospheres the temperature decreases slowly to 191° C at 9 atmospheres. A total decrease of 60° C is observed over the entire pressure range. Approximately 60 percent of the temperature drop occurs in the range of 1 to 2 atmospheres. Spontaneous ignition temperatures for pure paraffin fuels such as n-heptane approach 200° C at 12 atmospheres pressure (ref. 3). This is fairly close agreement with the present work considering the differences in technique.

The spontaneous ignition temperature at atmospheric pressure (250° C) compares favorably with determinations made by other researchers. In a similar apparatus, 247° C was reported (ref. 4); in a 35-cc flask 248° C was recorded (ref. 1); and reference 6 with a different type of apparatus reported 247° C. Even in systems with airflow where the fuel was added dropwise, spontaneous ignition temperatures were found to be 250° C (ref. 7) and 259° C (ref. 8).

2,2,4-Trimethylpentane (isooctane). - With the highly branched molecule of isooctane, the spontaneous ignition temperature was reduced from approximately 467° C to 231° C when the pressure was increased from 1 to 9 atmospheres (fig. 2(a)). The decrease of the spontaneous ignition temperature is quite rapid up to about 4.5 atmospheres, but markedly slower as the pressure is raised beyond this value. The total drop of the temperature for isooctane is about 230° C as compared with 60° C for n-heptane. From 1 to 5 atmospheres, the spontaneous ignition temperature decreases about 213° C, which is 92 percent of the total drop in temperature.

An experimental observation during the course of the determinations with isooctane indicates a difference between the ignitions occurring below approximately 5 atmospheres and those occurring above this pressure. When the fuel is injected into the flask, the temperature falls. Below 5 atmospheres, ignition occurred before the temperature returned to its original value. Above 5 atmospheres, ignition occurred after the temperature had risen above its original value. With isooctane-air mixtures, (ref. 5) there was a difference in the ignitions occurring above 4.85 atmospheres and those occurring below this pressure. These observations are consistent, and seem to suggest a change in the reaction mechanism at about 4.5 to 5.0 atmospheres.

The difference between the spontaneous ignition temperature for isooctane and n-heptane is 40° C at 9 atmospheres. In reference 5 at this same pressure, the difference was approximately 44° C. This agreement is quite good considering that the spontaneous ignition temperatures determined in reference 5 were with fuel-lean mixtures, whereas all the present work was done with fuel-rich mixtures. These workers also employed premixed fuel-air mixtures which were rapidly let into an evacuated heated bomb. The agreement suggests that the structural differences among hydrocarbons are reflected in the spontaneous ignition temperature at high pressures, in spite of the widely different methods, concentrations, and ignition chambers employed.

The spontaneous ignition temperature of isooctane at 1 atmosphere has been determined by many investigators. The values from the literature range from 418° (ref. 2) to 502° C (ref. 7). The value observed in this research is 467° C. The comparison can be considered fairly good since this fuel is quite sensitive to surfaces as compared with other hydrocarbon fuels (ref. 1). Reproducibility with isooctane in the present experiments was quite satisfactory; this is borne out by check points on the curve.

Benzene. - The spontaneous ignition temperature of benzene decreased from 626° C at 1 atmosphere to 350° C at 9 atmospheres. Inspection of figure 2(a) shows an abrupt break in the curve at roughly 4 atmospheres. At this pressure, at least eight attempts were made to obtain an ignition below the recorded temperature. Between 4 and 5 atmospheres a drop of about 100° C is observed that gives two distinct portions to the spontaneous ignition temperature - pressure curve. It can be seen that the rate of the temperature decrease is more rapid at the lower pressures.

This result is somewhat surprising since benzene has shown in previous work a regular decrease of the spontaneous ignition temperature with increasing pressure up to 30 atmospheres (ref. 3). With lean, premixed benzene-air mixtures, a very smooth curve was obtained from 1 to 10 atmospheres (ref. 5). In view of this very definite break in the spontaneous ignition temperature - pressure curve for this fuel, it is instructive to mention the difficulties encountered when attempting to reproduce points on the curve. As already mentioned, a Vycor flask was used with this fuel because the anticipated ignition temperature of benzene (600° to 700° C) closely approached the softening point of Pyrex.

When the tests began, the spontaneous ignition temperatures at the same pressure differed from time to time by as much as 20° or 25° C. After many experiments in the same flask, however, the data became more consistent. The check points shown in figure 2(a) are quite good since the determinations were made in a "seasoned" ignition chamber. Others have noted the difficulty of using benzene in this type of experiment (ref. 9). They believed that carbon deposition was responsible to a large extent for the erratic behavior of liquid benzene. Indeed, in the present work, a large amount of soot was formed on the ignition of benzene, especially, above 4 atmospheres.

Values of the spontaneous ignition temperature for benzene at atmospheric pressure have been reported as low as 559° C (ref. 1) and as high as 645° C (ref. 7). The spontaneous ignition temperature reported here (626° C) lies between these extremes, although much nearer the higher value.

JP-4 fuel. - Spontaneous ignition temperature - pressure curves for two samples of JP-4 fuel (A and B) are shown in figure 2(b). Samples A and B are from different batches of jet fuel. The shape of the curves is similar to that of n-heptane. The total decrease in the spontaneous ignition temperature for both A and B over the total pressure range was 62° C. At all pressures, a constant difference of 20° C between the spontaneous ignition temperature of these two samples was observed. The temperature difference is considered significant since the apparatus gives very reproducible results.

A careful inspection of the analysis sheets showed that there are no real differences in the properties of fuels A and B (see table II). Reference 10 presents a summary of data which shows that the spontaneous ignition temperature of many hydrocarbons can be raised significantly by the use of additives. Metallo-organic and polar compounds appear especially active in this regard. Therefore, an attempt was made to determine if the minor, nonhydrocarbon components, which are likely to be present in jet fuels, have an effect on the spontaneous ignition temperature.

This determination was made by percolating 1 liter of both JP-4 fuels (samples A and B) through 800 grams of silica gel. The spontaneous ignition temperature of sample B was lowered by approximately 10° C, while that of sample A was raised approximately 6° C at 9 atmospheres as shown in table II. The aromatic content of both fuels was decreased (see table II), and it is difficult to explain the above results on this basis. Whether polar constituents are responsible for the conflicting behavior is a question that cannot be answered, for it is not known whether the concentration of the polar compounds was the same in both samples before percolation through the silica gel.

JP-5 fuel. - In figure 2(c), the spontaneous ignition temperature - pressure curve for JP-5 fuel is shown. It bears a striking resemblance to the curves for JP-4 fuel. From 1 to approximately 3 atmospheres the spontaneous ignition temperature decreases fairly rapidly, but thereafter only a slight decrease is observed. The total drop in temperature is only 41° C as compared with 62° C for JP-4 fuel. In figure 2(c) are check points obtained from the same fuel sample more than a year earlier. No significant change is observed.

General Comparisons of All Fuels

Hydrocarbons. - The spontaneous ignition temperature of the hydrocarbons decreases in order of magnitude with increasing pressure as follows: Benzene (aromatic), isooctane (branched-chain paraffin), and *n*-heptane (straight-chain paraffin).

As mentioned previously, the behavior of fuels at low pressures is not the same as at high pressures. Heptane and isooctane differ by 217° C at 1 atmosphere but only by 40° C at 9 atmospheres. Benzene and heptane differ by 376° C at atmospheric pressure but only by 160° C at 9 atmospheres. However, such great differences do not exist with benzene and isooctane; at 1 atmosphere they differ by about 160° C and at nine atmospheres by 120° C. Thus, extrapolation of relative spontaneous ignition - temperature behavior from low pressures to high pressures can introduce serious errors.

Hydrocarbons and jet fuels. - It was shown that structural differences in pure hydrocarbons are reflected in their spontaneous ignition temperatures. The ignition temperatures for the hydrocarbons over the entire pressure range are of the same order as the total decrease of spontaneous ignition temperature with pressure, that is, aromatic > branched-chain paraffin > straight-chain paraffin.

From figure 2(d), it appears that both jet fuels are similar to n-heptane. In fact, the temperature decrease over the experimental pressure range for n-heptane and JP-4 fuel is almost the same (60° C). Although JP-4 fuel gave higher spontaneous ignition temperatures throughout, the curves are almost identical in shape. The less volatile JP-5 fuel yields a curve much closer to that of n-heptane. The similar values of the spontaneous ignition temperature at 1 atmosphere for JP-5 and n-heptane fuels are 247° and 250° C, respectively. Over the entire pressure range, they differ by only 10° C or less.

It is not surprising that JP-5 fuel gives lower spontaneous ignition temperatures than JP-4. References 1 and 4 have shown that high-molecular-weight hydrocarbons yield lower spontaneous ignition temperatures than do low molecular weight straight-chain compounds. The difference in the spontaneous ignition temperature of these jet fuels is only 25° C at 1 atmosphere, and this difference is almost eliminated at 9 atmospheres where they differ by only 6° C or less. The rate of change of the spontaneous ignition temperature with pressure becomes very small at pressures above 5 or 6 atmospheres.

Ignition-Lag Experiments with n-Heptane

The time lag before ignition may be a useful tool in anticipating fire hazards. It can be taken as the maximum time that a fuel may be held safely under certain conditions of the chamber and surrounding atmosphere.

Ignition lags have been employed in much theoretical speculation. For the simple thermal theory of spontaneous ignition, the ignition lag is proportional to the reciprocal of the reaction rate $1/\omega$ (ref. 11). If the concentration of reactants is constant, the rate of the reaction is proportional to $\exp(-E/RT)$ where E is the activation energy, R the gas constant, and T the temperature. Therefore $\tau \propto \exp(E/RT)$ where τ is the ignition lag in seconds. The logarithmic form of the equation is $\ln \tau = E/RT + C$.

A plot of ignition lag against reciprocal of temperature usually yields a straight line whose slope may be used to calculate the energy of activation. Such a plot is presented in figure 3 using the data shown in table III. Three fuel charges (i.e., 0.17, 0.37, 0.68 cc) were employed, and experiments were performed with each charge at three pressures.

The lines of figure 3 show some curvature. This was observed in other experiments (refs. 2, 12, and 13) and may be due to a change in the reaction mechanism with change in temperature. Also the assumed constant initial concentration may not be true.

From the slopes of the lines, the activation energy was calculated over a temperature range of 35° C. The energy remains essentially constant for the three fuel charges at all pressures. The following table shows the results over a temperature range of 220° to 255° C:

Charge, cc	Activation energy, kcal/mole			
	Pressure, atm			Ave.
	2.36	5.07	7.80	
0.17	23	20	27	23
.37	26	19	19	21
.68	23	20	16	20
Ave.	24	20	21	

The activation energy (over-all) for n-heptane appears to be about 21,000 calories per mole. At 1 atmosphere in the temperature range of 222° to 333° C, reference 2 reports 18,000 calories per mole for this fuel.

Increasing the pressure decreases the ignition lag. When the ignition lags at constant temperature for n-heptane (table III) were plotted against pressure on log-log paper, a curve rather than a straight line was obtained. Thus, determination of the pressure exponent n in the equation $\tau P^n = \text{constant}$ was not possible (where P is pressure).

In reference 14, a plot of ignition lag against reciprocal of temperature at 9, 15, and 20 atmospheres pressure in the range of 300° to 500° C is shown. The data are from adiabatic compression experiments and were gathered from several sources. A direct comparison of these results with those given herein cannot be made because of the higher temperatures and pressures of the adiabatic compression experiments. However, the general trends of ignition lag with temperature and pressure are very similar to those in this report.

SUMMARY OF RESULTS

Minimum spontaneous ignition temperatures for three hydrocarbons and two jet fuels were determined in air at pressures ranging from 1 to 9 atmospheres. The following results were obtained:

1. As the pressure was increased from 1 to 9 atmospheres, the spontaneous ignition temperatures decreased as follows: benzene, 626° C to 350° C; isooctane, 467° to 231° C; n-heptane, 250° to 191° C; JP-4 fuel, 272° to 210° C; JP-5 fuel, 247° to 206° C.

2. In general, the spontaneous ignition temperature decreased sharply as the pressure was raised from 1 to 3 or 4 atmospheres. At higher pressures, very little change took place.

3. Two different samples of JP-4 fuel showed a constant difference in the spontaneous ignition temperature of approximately 20° C over the entire pressure range. By percolating the fuels through silica gel the difference was reduced to 10° C.

4. The difference in the spontaneous ignition temperature of two fuels at a low pressure cannot be used for estimating the respective spontaneous ignition temperatures at higher pressures, because differences are greatly reduced when pressure is raised.

5. For n-heptane, a plot of time lag before ignition against the reciprocal of temperature yields a line with some curvature. The straight portion of the ignition lag - temperature curves for each of the three fuel charges at three pressures gave an average activation energy of 21,000 calories per mole.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 10, 1956

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TABLE I. - MINIMUM SPONTANEOUS IGNITION TEMPERATURE

FOR LIQUID FUELS AT VARIOUS PRESSURES

Pressure,		Temperature,		Fuel charge, cc	Time lag,	
lb/sq in.	atm	°C	°F		sec	min
			n-heptane			
0	1.00	250	482	0.10	5.4	0.09
10	1.68	213	415	.37	66.0	1.10
20	2.36	210	410	.74	96.0	1.60
40	3.72	206	403	.62	47.4	.79
60	5.07	200	392	.74	51.6	.86
80	6.45	195	383	1.07	82.2	1.37
100	7.80	191	376	1.36	103.2	1.72
120	9.15	191	376	1.24	66.0	1.10
			Isooctane			
0	1.00	467	872	0.08	6.0	0.10
14	1.95	355	671	.17	5.4	.09
20	2.36	310	590	.25	8.4	.14
40	3.72	270	518	.62	24.0	.40
60	5.07	253	487	.62	39.6	.66
80	6.45	243	469	1.07	80.4	1.34
100	7.80	237	458	1.07	84.0	1.40
117	8.95	231	448	1.07	76.8	1.28
			Benzene			
0	1.00	626	1157	0.08	8.4	0.14
20	2.36	544	1011	.37	18.0	.30
40	3.72	500	932	.37	31.2	.52
60	5.07	385	725	.37	43.2	.72
80	6.45	360	680	.37	34.8	.58
100	7.80	346	655	.37	25.8	.43
116	8.90	360	680	.37	20.4	.34
			JP-4			
0	1.00	272	522	0.08	6.0	0.10
20	2.36	235	455	.37	46.2	.77
40	3.72	224	435	.50	73.8	1.23
60	5.07	219	426	.62	78.0	1.30
80	6.45	217	423	.74	74.4	1.24
100	7.80	210	410	1.07	106.2	1.77
116	8.90	210	410	1.07	101.4	1.69
			JP-5			
0	1.00	247	477	0.08	9.6	0.16
20	2.36	215	419	.50	73.8	1.23
40	3.72	210	410	.62	75.0	1.25
60	5.07	206	403	.62	50.4	.84
80	6.45	206	403	.62	52.8	.88
100	7.80	202	396	.62	42.0	.70
116	8.90	206	403	.62	10.8	.18

TABLE II. - ANALYSIS DATA FOR JP-4 FUEL BEFORE AND AFTER PERCOLATION THROUGH SILICA GEL

Property	Fuel A		Fuel B	
	Before	After	Before	After
Initial boiling point, °F	144		152	
Final boiling point, °F	474		482	
Reid vapor pressure, lb/sq in.	2.6		2.3	
Hydrogen-carbon ratio	0.168		0.171	
Heat of combustion, cal. (est.)	18,675	18,775	18,725	18,825
Aniline point, °F	139.3	159.8	141.1	162.3
Molecular weight	134		131	
Stoichiometric fuel-air ratio	0.0677		0.0675	
Aromatics, volume percent	11.4	5.0	10.3	1.3
Spontaneous ignition temperature, °C, at -				
1 atm	252	260	272	273
9 atm	188	194	210	200

TABLE III. - TIME LAGS BEFORE IGNITION FOR n-HEPTANE WITH THREE FUEL CHARGES AT THREE PRESSURES

Temperature, °C	Pressure, atm								
	2.36			5.07			7.80		
	Fuel charge, cc								
	0.17	0.37	0.68	0.17	0.37	0.68	0.17	0.37	0.68
	Ignition lag, sec								
270	----	----	3.0	----	----	----	----	----	----
260	3.0	3.6	4.8	----	2.4	2.7	----	----	----
250	4.2	5.7	7.2	2.7	3.3	4.5	1.2	2.1	3.0
240	6.6	8.4	10.5	3.9	4.2	7.2	2.4	3.0	4.2
230	11.1	15.3	17.4	6.0	6.9	10.2	4.2	4.5	5.7
225	----	----	23.4	6.6	----	----	----	----	----
220	19.8	24.3	----	10.2	10.5	17.1	7.2	7.5	9.3
217	----	----	----	13.5	----	----	9.3	----	----
210	----	----	----	----	23.1	35.1	----	13.2	18.3
206	----	----	----	----	----	----	----	19.8	----

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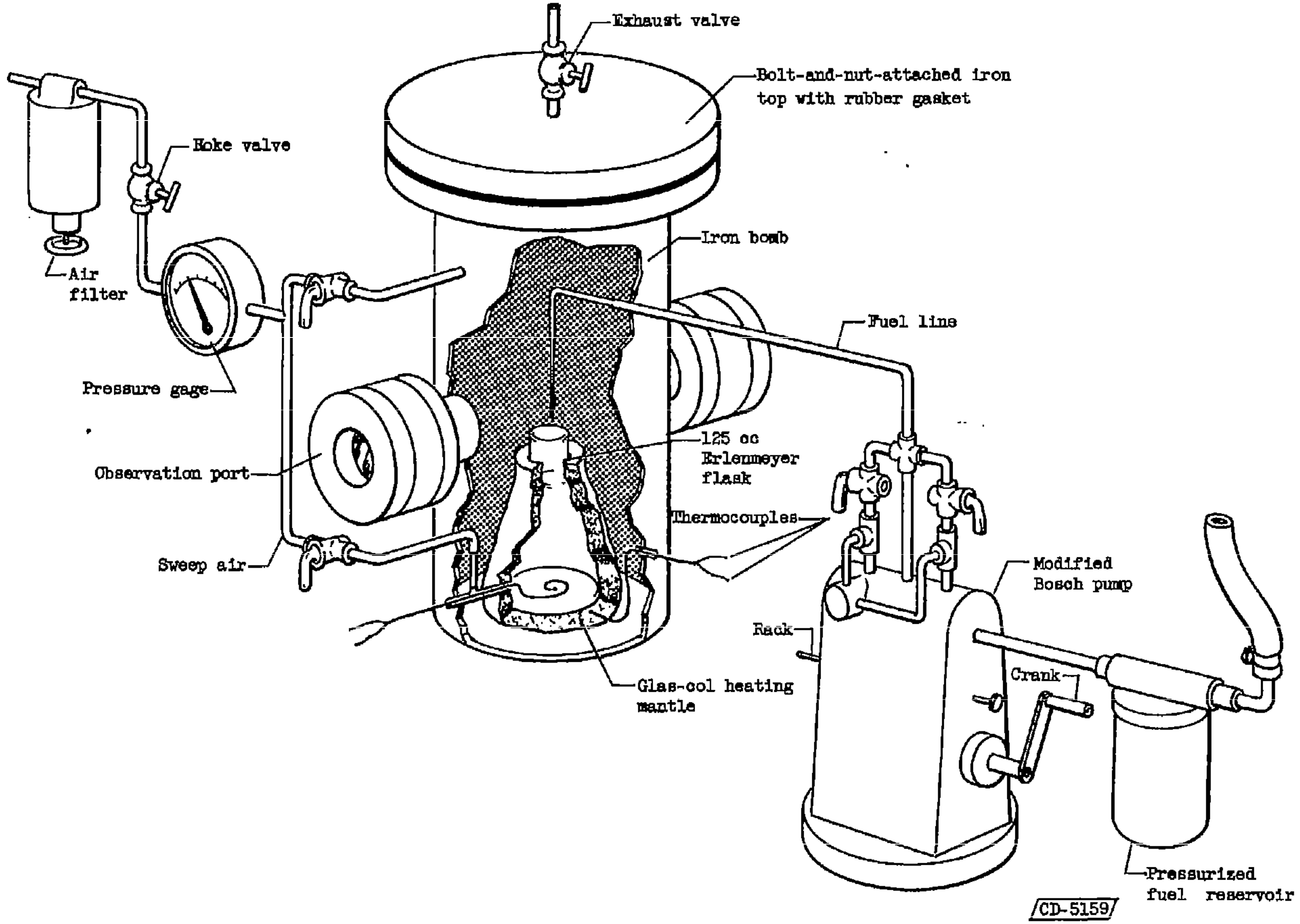

Figure 1. - Spontaneous ignition temperature apparatus for high pressures.

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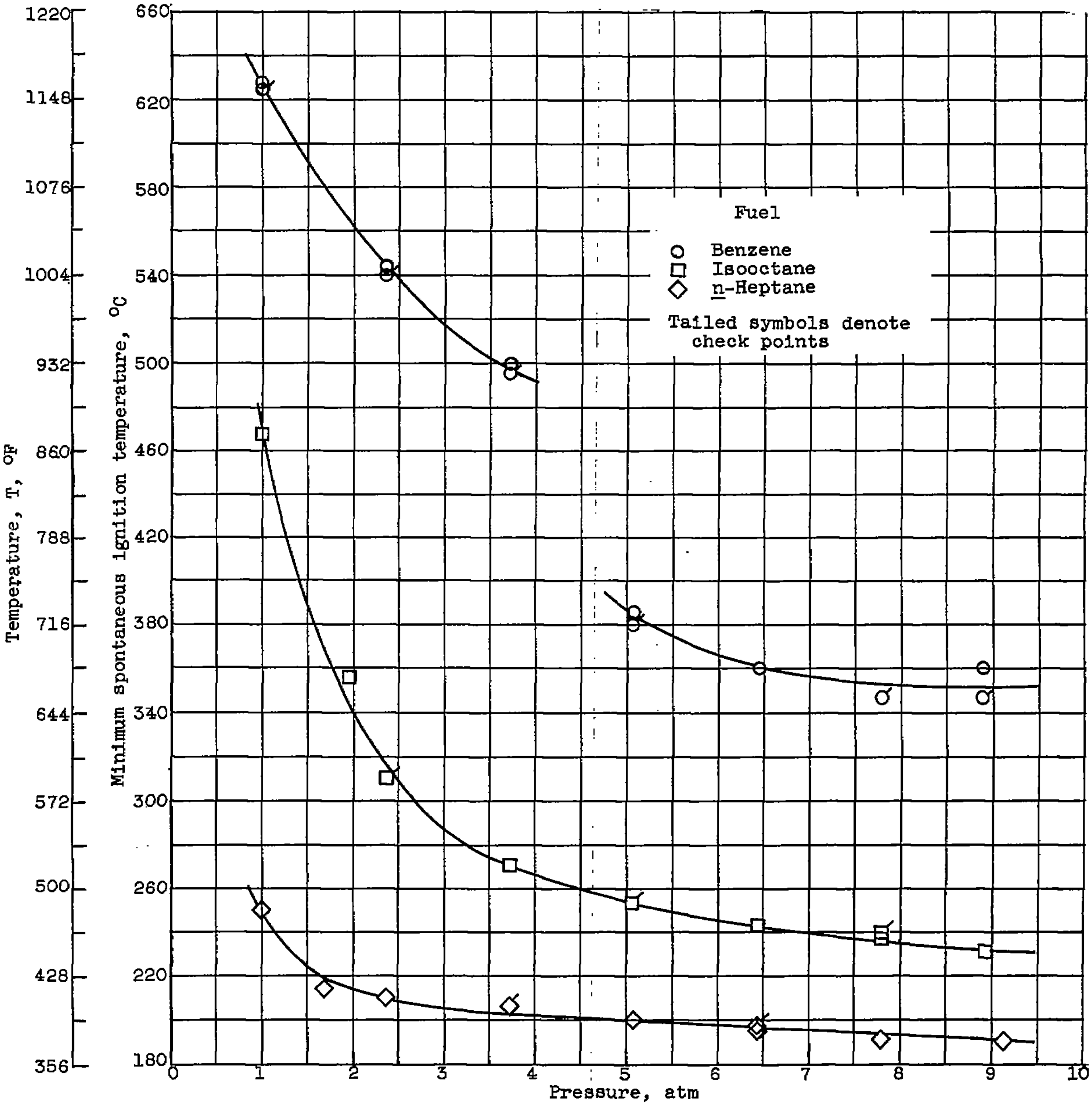
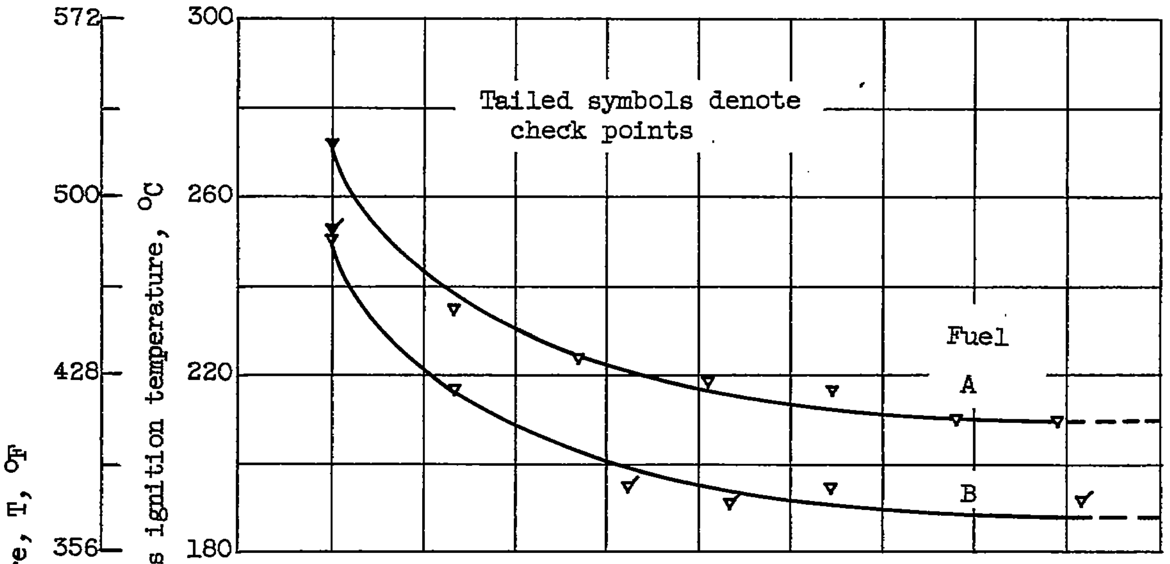
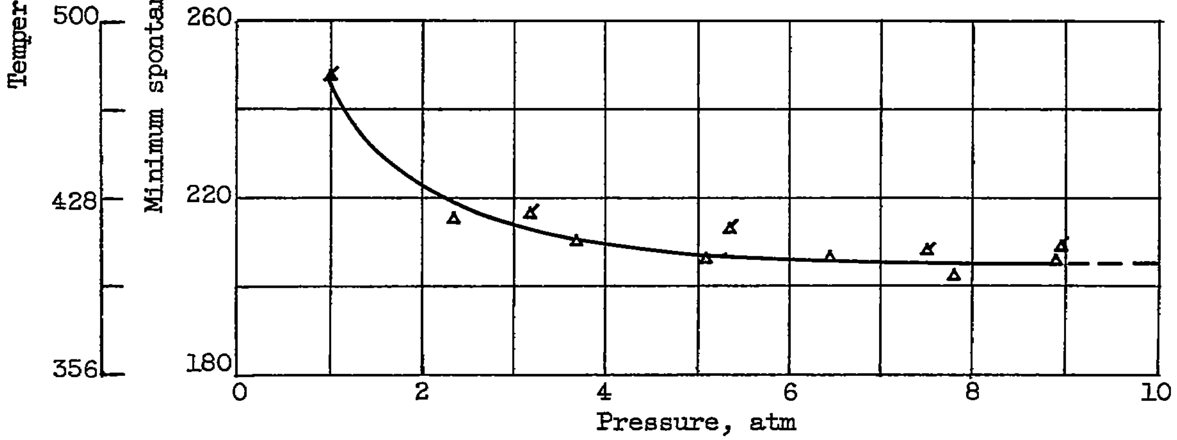


(a) Pure hydrocarbons.

Figure 2. - Effect of pressure on spontaneous ignition temperature of liquid fuels in air.

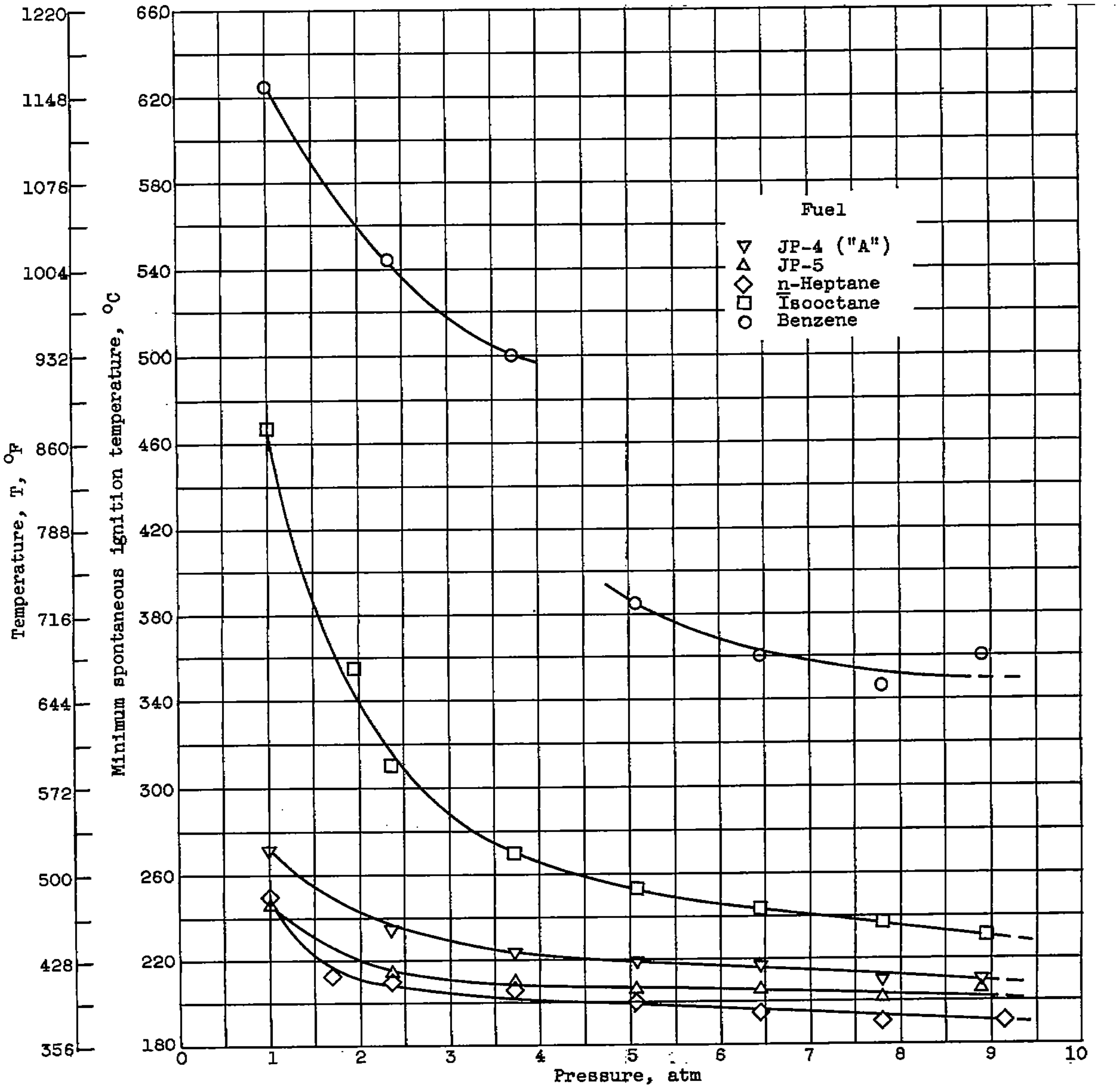


(b) JP-4 fuel.



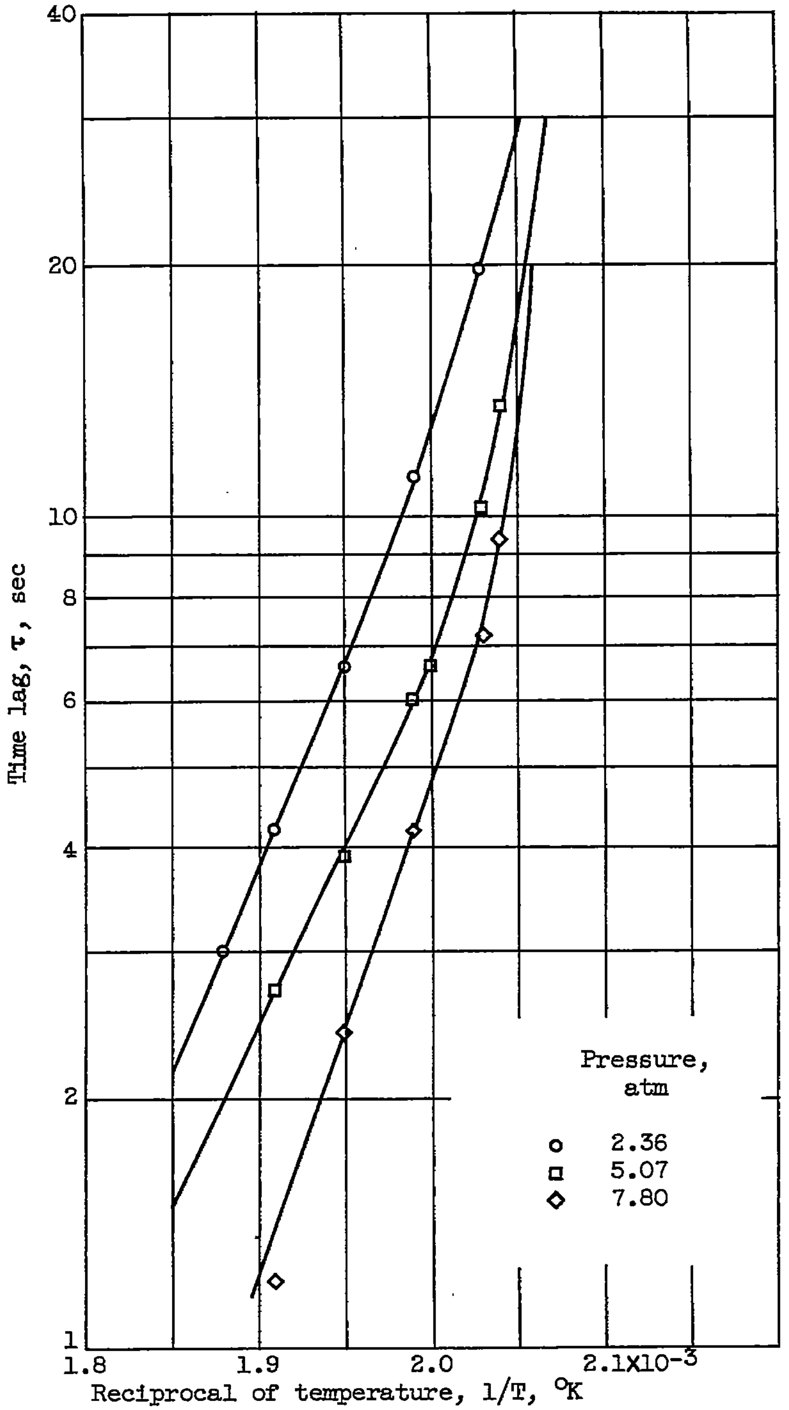
(c) JP-5 fuel.

Figure 2. - Continued. Effect of pressure on spontaneous ignition temperature of liquid fuels in air.



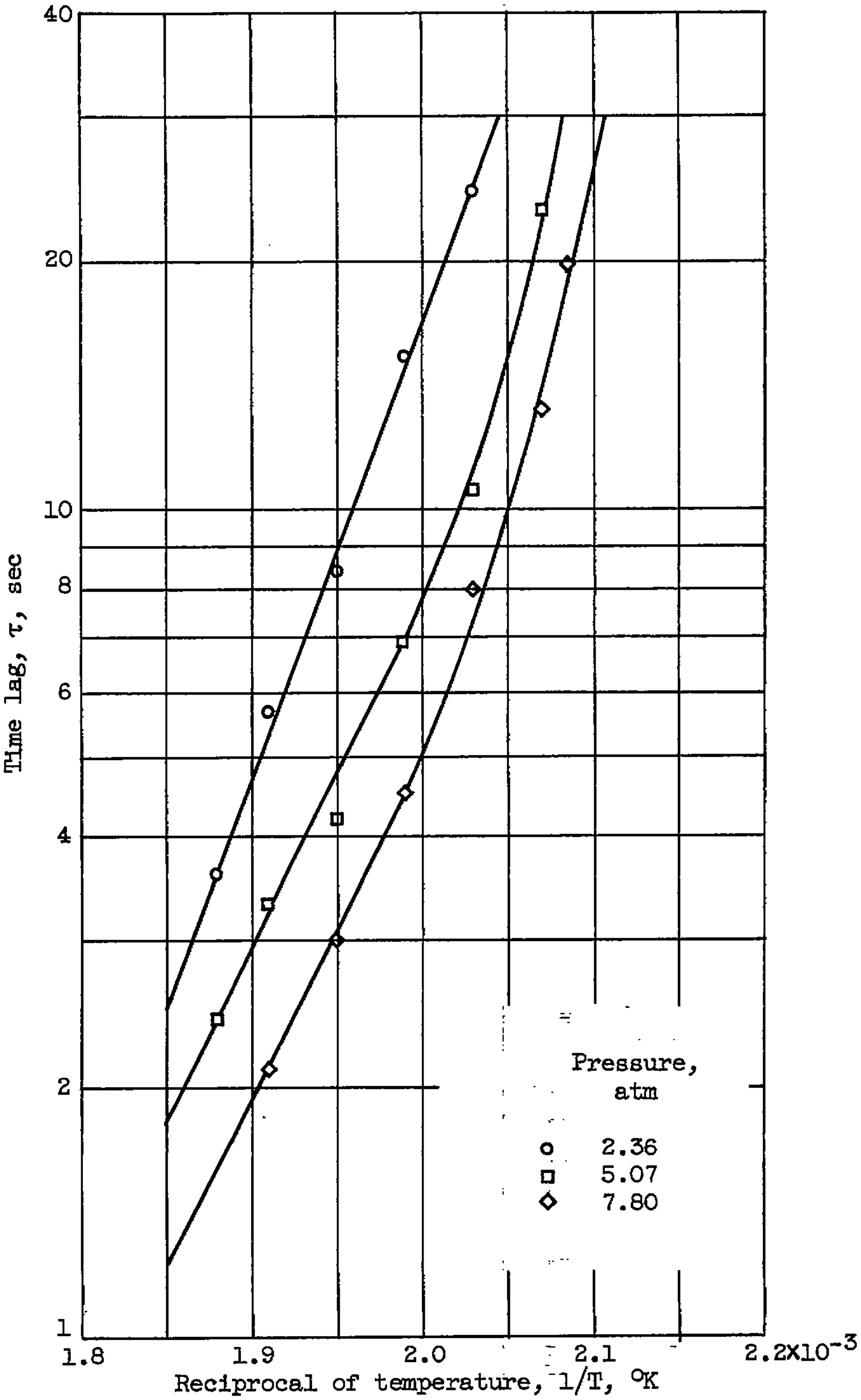
(d) All fuels.

Figure 2. - Concluded. Effect of pressure on spontaneous ignition temperature of liquid fuels in air.



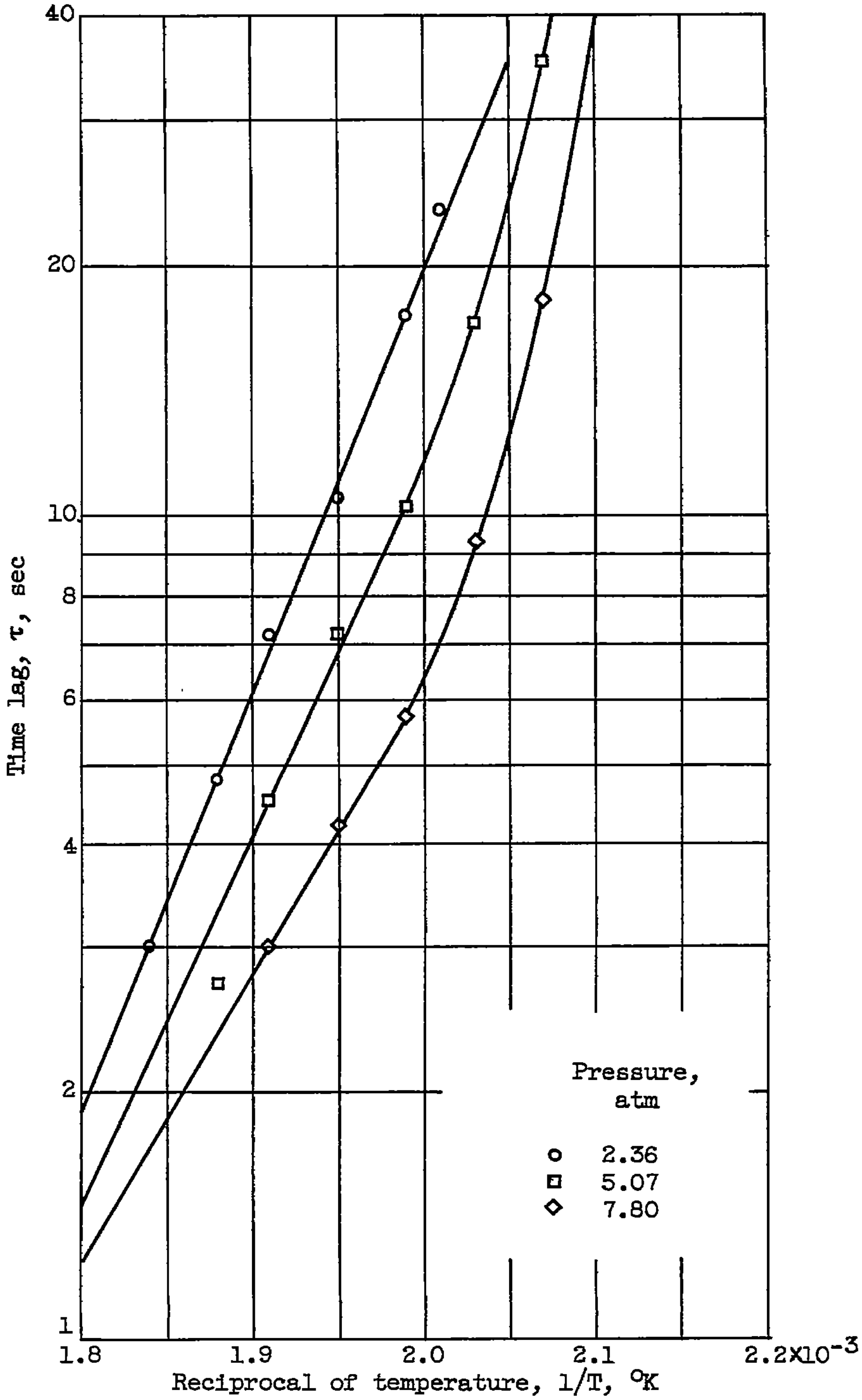
(a) Fuel charge, 0.17 cubic centimeter.

Figure 3. - Time lags before ignition as a function of reciprocal of temperature for n-heptane in air at various pressures.



(b) Fuel charge, 0.37 cubic centimeter.

Figure 3. - Continued. Time lags before ignition as a function of reciprocal of temperature for n-heptane in air at various pressures.



(c) Fuel charge, 0.68 cubic centimeter.

Figure 3. - Concluded. Time lags before ignition as a function of reciprocal of temperature for n-heptane in air at various pressures.

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