[redacted]

TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 924

MODERN METHODS OF FUEL TESTING

By F. Seeber

Luftfahrtforschung
Vol. 16, No. 8, August 20, 1939
Verlag von R. Oldenbourg, München und Berlin

Washington
December 1939

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 924

MODERN METHODS OF FUEL TESTING*

By F. Seeber

The knock rating of aviation fuels by the conventional octane scale in the CFR engine is defective and proceeds from misleading premises.

After a brief survey of the commonly used single-value test methods, the importance of the determination of the incipient knock for the octane number is discussed and improvements suggested for the knock testing in the CFR engine. But the difficulty of transferring the findings from the test engine to single-cylinder and multicylinder airplane engines is still unsolved.

The DVL supercharge test method with its superiority of direct determination of fuel knock in each single cylinder of an airplane engine without involving structural changes, is described and the advantages of a multiple-value method enumerated. Owing to the far-reaching adaptability of the test conditions of the supercharge method to the conditions of flight operation, a diagrammatic presentation of the knock characteristics is made possible, which is of great significance for the further development of high-output aircraft engines and their fuels.

INTRODUCTION

The demands made on aviation fuels for high take-off power and for low fuel consumption at comparatively high cruising powers are, as is known, limited by the fuel knock in spark-ignition engines. High engine powers are most favorably achieved by higher mean effective pressures. The latter are most severely affected by the octane number of a fuel, according to Ellor (reference 1). But, tried out in the airplane engine, it was found that the rating of knock tendency by octane number under fixed test conditions, is insufficient and may lead to erroneous conclusions. The remedy called for new scales of appraisal, which are described in the present report. The treatment,

*"Neuere Verfahren der Kraftstoffprüfung." Luftfahrtforschung, vol. 16, no. 8, August 20, 1939, pp. 431-437.

however, is confined exclusively to the short-time tests in single-cylinder assemblies; any discussion of the testing of fuel-endurance behavior would be premature, since this test is still in the experimental stage.

KNOCK TESTING IN THE CFR ENGINE

a) Rating by Octane Number

The knock rating of aviation fuels is at present almost exclusively carried out in the CFR engine, and in Germany, of late, in the I.G. test apparatus. In both the fuel is made to knock by changing the compression ratio. The intensity of the knock, which is maintained in these tests, is defined for a certain deflection on the knock meter.

The knock characteristics of the test fuel are, as is well known, compared with those of blends from reference fuels - the standard reference fuels being iso-octane and n-heptane. The knock rating of iso-octane was arbitrarily set at 100, and that of n-heptane at 0.

Thus the knock rating of fuels today is by means of the octane number; i.e., the amount of iso-octane of a blend of iso-octane and n-heptane which, under certain test conditions has the same knock characteristics as the fuel to be tested.

Since this test was chiefly intended as a check on the fuel manufacture and therefore on the uniformity of the delivered product, it was believed that the testing of the knock characteristics of the various fuels could be effected without recording pressure, temperature, or heat transfer.

The following test methods are in present use (reference 2):

1. CFR research method (Italy)

2. CFR and I.G. engine methods, respectively (Germany)

3. Modified CFR engine method (England, France)

4. CFR low-temperature method (U.S.A.)

5. CFR-L 3-method (U.S.A.)

6. U.S. Army test method in modified CFR engine (U.S.A.)

All these methods confine themselves to one single characteristic value which, with the exception of the U.S. Army method, is determined at a comparatively severe knock. The test conditions of the methods differ from one another only in the inlet-air temperatures, in the mixture ratio, or in the r.p.m.

All the named single-value methods, even if they rate the fuels occasionally at different requirement stages, were - by themselves - no useful indication, since fuels of the same octane number frequently manifested a widely varying knock behavior in practical flight-operating conditions. This applies in particular measure to aviation fuels of class OZ 87 and over.

b) Discussion of Octane Rating

The cause of the defective determination of the knock tendency of different fuels by these test methods is to be found almost exclusively in the erroneous assumption that the testing under one single - even if under always rigidly prescribed - test condition, would be sufficient to draw conclusions for all other fuel requirements. The greatly changing temperature, pressure, and heat-transfer conditions in flight operation cannot be reproduced by the change of one single test condition - even if the established value is obtained at the air-fuel ratio corresponding to the greatest knock intensity.

As attractive and advantageous as a single-value method seemed at first in regard to the short test period, the cheapness of the method and the small amount of fuel needed for a test - as the best solution for the knock rating of fuels - the results proclaimed the need for a multiple-value rating, which ultimately leads to the diagrammatical presentation of the knock rating of fuels. In the opinion of the DVL, the conventional rating by octane number has the following defects:

1. The rating is achieved at a too severe knock, as

confirmed in the DVL tests (reference 3) made in 1934-35. In these experiments the different aviation fuels - while retaining all test specifications of the CFR engine method - the incipient knock, i.e., the compression ratio at which the first uniform audible knock occurred, was ascertained (fig. 1). It is merely pointed out in this connection that straight-run fuels with a knock characteristic of over 100 octane units - which prove of predominantly aromatic character, such as pure benzol, for example - possess, under the requirements of the CFR engine method (mixture temperature 150° C.), a far earlier incipient knock than leaded benzene-like fuels, despite the fact that the compression ratios were the same in all cases. This fact was affirmed by supercharge tests.

2. The determination of the octane number at only one-mixture temperature does not reproduce the temperature susceptibility of the fuel. This fact is disclosed by the different discrepancies of the research- and engine-octane numbers of 87-octane fuels of different chemical composition.

Fuels predominantly

	olefinic	aromatic	naphthalenic	paraffinic
Research OZ	98.5	93.6	88.0	88.0
Engine OZ	87.2	86.5	85.5	86.3
Difference in octane units	11.3	7.1	2.5	1.7

3. The testing at only one-mixture ratio, conditioned by the maximum deflection of the knock indicator agreed upon, is insufficient for rating a fuel (fig. 2, and reference 4). The testing of 87-octane fuels over the entire practical mixture range discloses the knock characteristic of leaded gasolines, especially by excess fuel, to be far greater than that of the standard and substandard reference fuels. Figure 3 illustrates the test data over the entire mixture range for 80- and 100-octane fuels at 80° and 130° C. mixture temperatures.

4. Lastly, the use of the conventional standard and substandard reference fuels for very knock-resistant fuels leads, because their temperature response is unlike that

of leaded gasolines to erroneous knock rating, as seen from the earlier picture (fig. 2). The use of leaded reference gasolines should remove this drawback.

c) Formulation of Octane Rating and New Rating Scales for the Concept of Knock Tendency

The testing of aviation fuels in the CFR engine probably fares much better if, as suggested elsewhere (references 9 and 10), the fuel knock is recorded:

a) at different inlet and mixture temperatures, respectively; for instance, at 50°, 100°, and 150° C.;

b) for different mixture ratios;

c) at incipient knock or, at any rate, at a less severe knock than that of the CFR engine method.

These tests could be made forthwith, with the compression ratio as variable, but other scales have also been proposed. Thus Boerlage suggested the allowable boost pressure at incipient knock (reference 5); Evans, Dodd, and Garner (reference 6), the maximum combustion pressure measurable at incipient knock. What the correct procedure will be nobody knows, since the problem of finding a correct knock-rating scale in a knock-test engine, is rendered difficult by:

1) the difficulty of ascertaining the same rating quantity even in structurally identical test engines for an identical fuel under identical test conditions (reference 7);

2) the uncertain transferability of the data to the single-cylinder or multicylinder aircraft engine as a result of not knowing the actual operating requirements in the aircraft engine.

KNOCK-RESISTANCE TESTS IN THE SINGLE CYLINDER

a) Advantages of Supercharge Test

The lack of agreement in fuel rating for practical flight operation in the CFR engine, prompted the DVL also to rate the fuel knock according to modern viewpoints. Since, first of all, the question of transferability of the CFR data to the aircraft engine remained unanswered, the urgency of the problem of determining the knock tendency of fuels as definitely as possible for aircraft-engine conditions, suggested a test procedure in single cylinders. Boerlage's proposed choice of boost pressure as variable, seemed the most favorable since it permitted the determination of the knock tendency of fuels in any desired single cylinder under conditions similar to those of the complete engine without requiring structural changes.

b) Determination of Knock Limitation

The development of the knock test showed that the knock intensity maintained in the octane rating in no way resembled the requirements of the fuel in an aircraft engine. The occurrence of the very first knock impacts - i.e., the incipient knock, constitutes a moment of danger for the aircraft engine, and for this reason the DVL supercharge method chose the incipient knock as the indication for the knock intensity. Since the present state of development of the indicators makes the determination of the incipient knock a complicated and drawn-out procedure, the audible method was at first employed. According to the experiences of the DVL, this incipiency is best represented by six to ten sharp knocks per minute. The accuracy of the method is ±15 mm Hg. The supercharge power was disregarded.

c) Choice of Test Conditions

To make the supercharge method definitely superior to the octane-rating method, the selection of the test conditions had to be made with due consideration to the conditions of the complete engine.

The fuels of modern high-output aircraft engines must have, first, a high take-off power, i.e., high mean effective pressure at full throttle performance. Accordingly, the supercharge test should include a run at:

a) starting speed;

b) with approximately 20-percent excess fuel;

c) the inlet air temperatures corresponding to the supercharger installation for the different design types.

Fuels for high-output aircraft engines must, further, have good leaning properties -- i.e., correspondingly high m.e.p. in the throttling range or, in other words, a test at:

a) cruising flight r.p.m.;

b) highest possible excess of air;

c) respective inlet-air temperatures.

Hence the supercharge test has to be made under various conditions. For tests in the air-cooled BMW 132 single-cylinder, the conditions were as follows:

1. Speed at 1,600 r.p.m. because of the audible method and saving of the engine, since testing at the knock limit at higher r.p.m. in OZ 87 engines, would result in serious disturbances. Although this r.p.m. does not correspond to the starting conditions, it could be proved in a large number of tests that the order of rating for different fuels at different r.p.m. was the same. Hence the low speed is in nowise objectionable.

2. The mixture ratio was chosen for a range from $\lambda = 0.7$ to 1.3, thus comprising the conditions of excess richness to greatest possible leanness.

3. Inlet-air temperatures at 35°, 80°, and 130° C.

4. For testing the best spark advance, achieved with excess air factors $\lambda = 0.7$, 0.9, 1.1, and 1.3 for knock-free combustion. (Further details may be found in Luftfahrtforschung, vol. 16, no. 1, 1939 (reference 8)).

d) Effect of Test Conditions on the Superchargeability of 87-octane Fuel

The results of the DVL supercharge test method are now discussed. Figure 4 gives the limiting curves of the allowable mean effective pressure of a commercial aviation gasoline that characterizes the CFR engine method with octane No. 87 for different inlet-air temperatures (35°, 80°, 100°, and 130° C.) plotted against the excess air. The lines of equal specific fuel consumption are included.

Figure 5 indicates the changes in mean effective pressure (in percent of rated power) for the limiting curve of an 87-octane fuel under the previously cited DVL conditions at:

1. 1,200 and 2,000 r.p.m.;

2. 35° and 130° C. inlet-air temperatures.

Figure 6 illustrates the effect of:

1. a 25-percent throttle setting;

2. change of number of knocks (zero);

3. spark advance to 40° crank setting on the displacement of the original limiting curve.

It is noted in passing that no identification of incipient knock was possible with the help of the pt diagram or its first derivative. Measurements of the absolute incipient knock with the aid of the second differential quotient (equation 12) confirm, however, the permissible superchargeability obtained by the audible method (fig. 7). These measurements were made in the CFR engine. The results with the BMW 132 single-cylinder are shown in figure 8. The test point obtained by the audible method lies in the bend of the characteristic curves of $\frac{d_2 p}{dt^2}$ for $\lambda = 0.75$, 0.9, and 1.0. These experiments were made by the Institute for Fuel Research in collaboration with F. Lichtenberger, and are to be continued so as to yield a quick and simple determination of the incipient knock, independent of audition. U.S. supercharge tests by Rothrock and Biermann (reference 11) - who also determined the incipient knock by the electrical method - likewise disclosed a parallel course to the limiting curves defined by audible knock.

While the test data cited so far were obtained in a 3.06-liter engine, figure 9 shows the superchargeability of an 87-octane fuel under different operating conditions in a 2-liter liquid-cooled single-cylinder test engine. The order of the effects of the different operating conditions on the allowable superchargeability and mean effective pressure (in percent of the rated power) is as follows:

1. Compression ratio
2. Spark advance
3. Excess air
4. Inlet-air temperature
5. Coolant temperature
6. Revolutions per minute

What effect the size of the swept volume under dissimilar cooling has on the allowable superchargeability in relation to excess air may be seen from the four examples illustrated in figure 10.

Other results for single cylinders of different design type made in the DVL by Dr. Berg, are omitted for lack of space.

e) Allowable Superchargeability of Fuels of Equal Octane Number - Their Chemical Composition

The significance of the chemical composition of fuels for the obtainable allowable boost pressure is of particular interest for the development of aviation fuels as illustrated on a few selected examples. Figure 11 shows the relation of allowable superchargeability of three chemically dissimilar 87-octane fuels to the mixture ratio under identical test conditions in a liquid-cooled single-cylinder engine. The high superchargeability of strongly aromatic fuels, especially with considerable excess richness, is plainly apparent while on leaning with increasing aromatic content of the fuels, a more profound reduction of the limiting curves is noticeable in contrast to the paraffinic-naphthylic fuels. Figure 12 shows the relation of allowable boost pressure to inlet-air temperature with $\lambda = 0.9$ for the same fuels. These tests reveal, aside from the superiority of aromatic fuels at low inlet-air temperatures, their great temperature susceptibility. Fuels of paraffinic-naphthalenic nature have far more temperature stability.

Figure 13 shows the extreme areas of obtainable m.e.p. (in percent of rated power) at equal number of knocks plotted against excess air and inlet-air temperature for 87-octane fuels. The effect of the dissimilar chemical composition of the fuels is readily apparent. Figure 14 is the graph for two 100-octane fuels and manifests the temperature susceptibility of the aromatic fuel. In spite of the identical octane number of the paraffinic fuel and its minor temperature relation, its superiority is slight and, at that, confined to the excess air range at very high inlet-air temperatures. The correctness of this rating was confirmed in recent aircraft-engine tests.

THE SIGNIFICANCE OF THE DVL SUPERCHARGE TEST METHOD IN PRACTICE

The correlation of the supercharge test at several inlet-air temperatures with the octane numbers obtained by various methods, affords the conditions illustrated in figures 15 and 16. A similar result is obtained from a comparison of the differences of the research- and engine-octane number with the differences of the allowable boost pressure at different inlet-air temperatures and $\lambda = 1.05$ excess of air. It means, in other words, that the rating of fuels in the CFR engine by any method, does not simulate their requirements in the single cylinder.

With the newly developed DVL supercharge method, on the other hand, a rating is offered that corresponds to the actual requirements.

Its chief advantages are as follows:

1. The knock tendency of fuels is tested direct in actual engine cylinders.

2. The fuels are tested under conditions most closely approaching actual service.

3. The rating by several values permits conclusions for the development of 100-octane engines and fuels.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

REFERENCES

1. Ellor, J. E.: Einige Aufgaben bei der Aufladung von Flugmotoren. Jahrbuch 1939 der Deutschen Luftfahrtforschung, Erganzungsband S. 200.

2. Seeber, F.: Kraftstoffe für Flugmotoren. Luftwissen, Bd. 5, Nr. 9, Sept. 1938, S. 321-330.

3. Seeber, F.: Über die Beziehungen zwischen motorischen Verhalten von Kraftstoffen und den Betriebsbedingungen. Luftwissen, Bd. 3, Nr. 11, 1936, S. 326-328.

4. Seeber, F.: Klopffestigkeitsprüfungen an Otto-Motoren RDT, Bd. 18, Nr. 39, 1938, S. 2.

5. Boerlage, G. D., Peletier, L. A., and Tops, J. L.: The "Allowable Boost Ratio." A New Method of Knock Rating for Aviation Fuels of High Antiknock Value. Aircraft Engineering, vol. 7, no. 82, 1935.

6. Evans, E. B., Dodds, E. M., and Garner, F. H.: The Nature of the Octane Scale. Jour. of the Inst. of Petroleum Tech., vol. 21, no. 146, 1935, pp. 1000-1012.

7. Philippovich, A. von: Der Verbrennungsvorgang im Explosionsmotor. Luftfahrtforschung, Bd. 13, 1936, S. 199-209.

8. Seeber, F.: Prüfung hochklopffester Kraftstoffe im Flugmotoren-Einzylinder. Luftfahrtforschung, Bd. 16, Nr. 1, 1939, S. 18-20.

9. Philippovich, A. von: s. Aussprache S. 20-21, Protokoll über die 7. Hauptsitzung des Comitees ISA 20 (Luftfahrt), Berlin, June 24-27, 1938.

   Becker, A. E.: Effect of Test Conditions on Fuel Rating. S.A.E. Jour., vol. 42, 1938, pp. 62-72.

10. Bass, E. L.: Prüfung von Kraftstoffen für Hochleistungsflugmotoren. Luftfahrtschrifttum des Auslandes in Übersetzungen, Bd. 3, Nr. 1, 1937.

11. Rothrock, A. M., and Biermann, Arnold E.: Engine Performance and Knock Rating of Fuels for High-Output Aircraft Engines. T.N. No. 647, N.A.C.A., 1938.

12. Lichtenberger, F., and Seeber, F.: Beitrag zur Frage der Klopfmessverfahren. A.T.Z., Heft 14, 1938, S. 372-374.

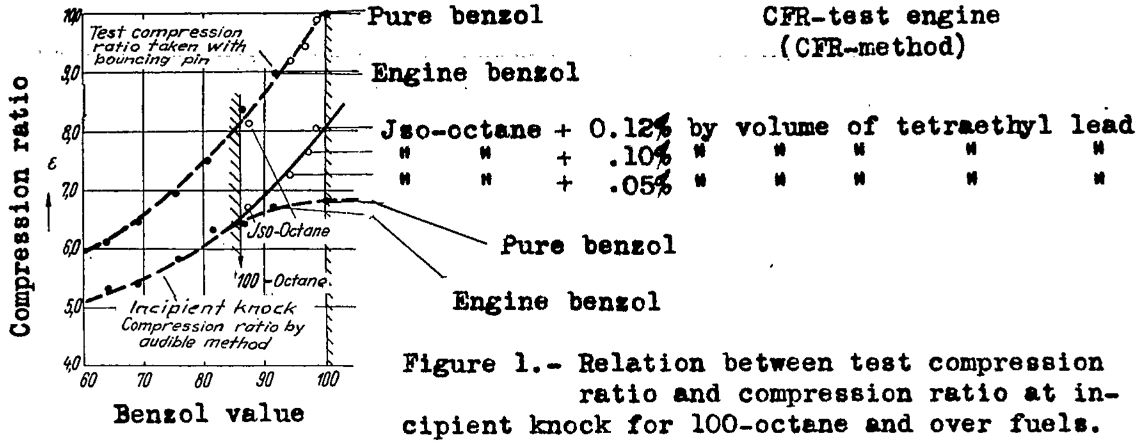


Figure 1.- Relation between test compression ratio and compression ratio at incipient knock for 100-octane and over fuels.

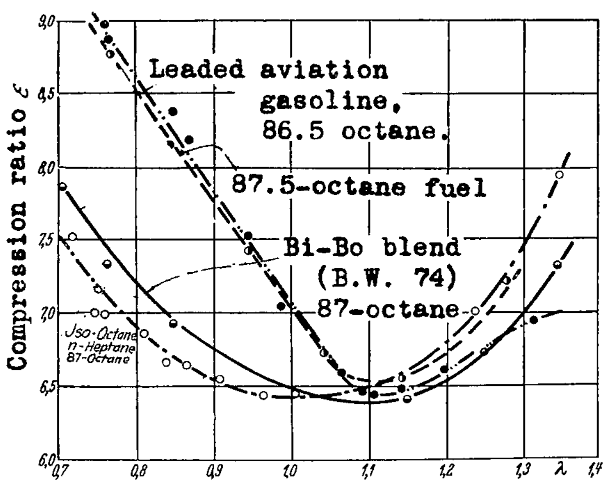


Figure 2.- Knock characteristics at different excess air, CFR motor.

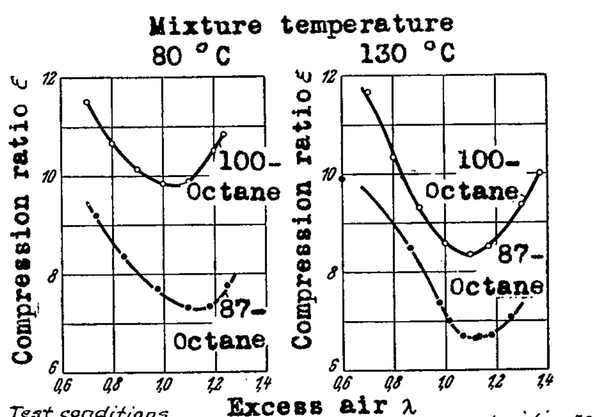


Figure 3.- Knock characteristics of 87-and-100-octane fuels at different excess air factors.

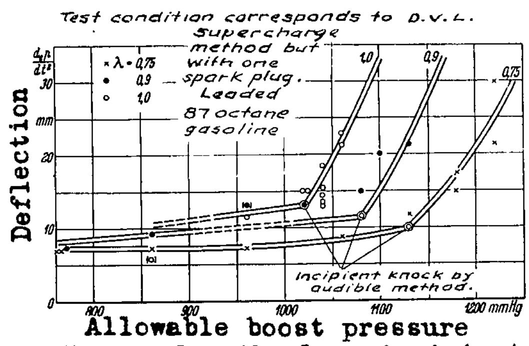


Figure 8.- Absolute incipient knock in BMW 132 single cylinder engine.

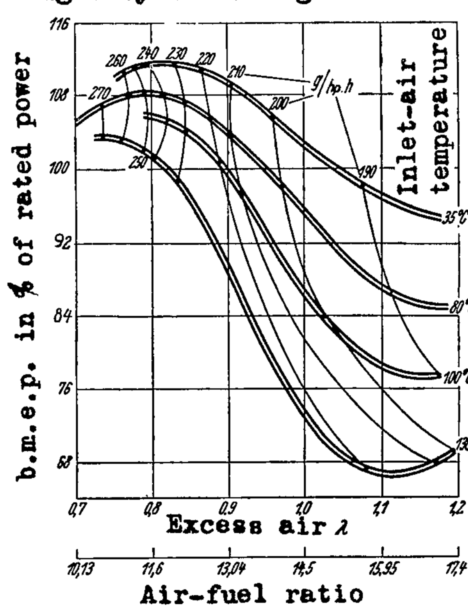


Figure 4.- Testing of 87-octane fuel by DVL supercharge method.

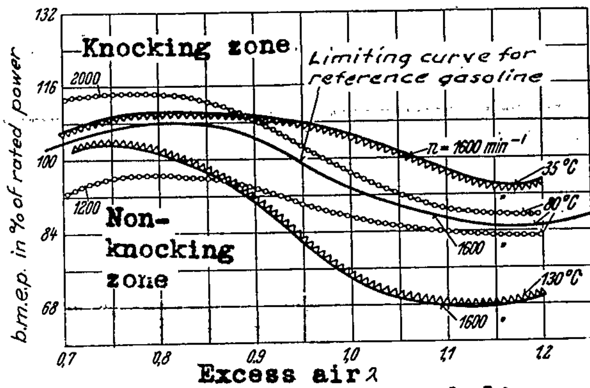


Figure 5.- Effect of knock limitation curve as a result of changed r.p.m. and inlet air temperature.

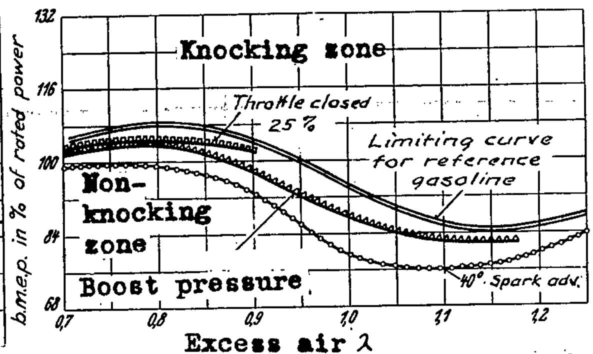


Figure 6.- Effect of changed throttle setting, number of knocks and spark advance on the knock limitation curve.

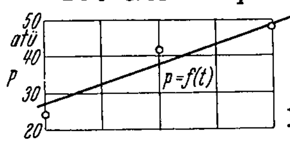
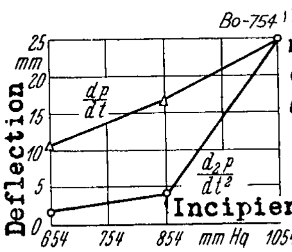


Figure 7.- Record of absolute incipient knock by means of pressure acceleration (2. derivative of p.t. diagram) in the CFR engine.



Incipient knock by audible method

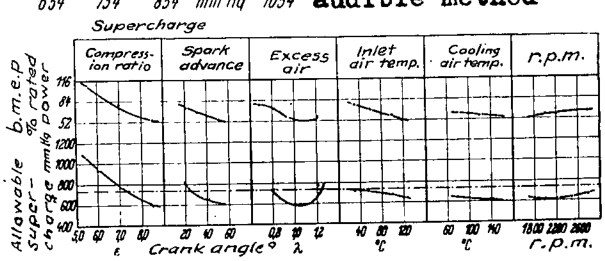


Figure 9.- Superchargeability of 87-octane fuel under different operating conditions.

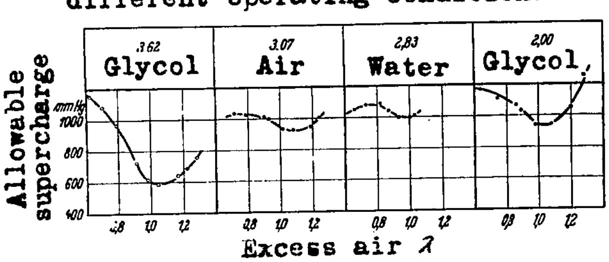


Figure 10.- Superchargeability of 87-octane fuel in different single-cylinder engines.

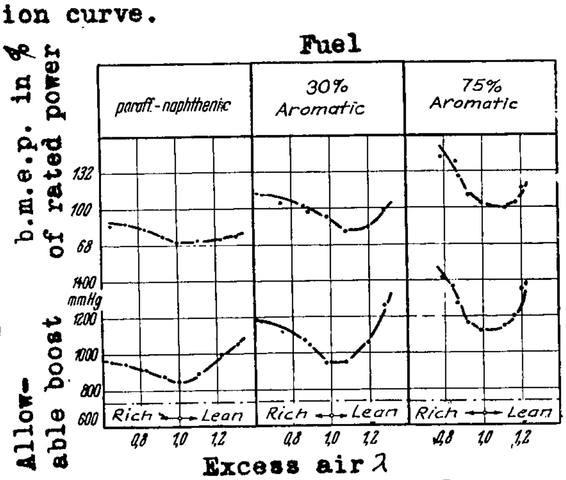


Figure 11.- Superchargeability of 87-octane fuels of different chemical composition.

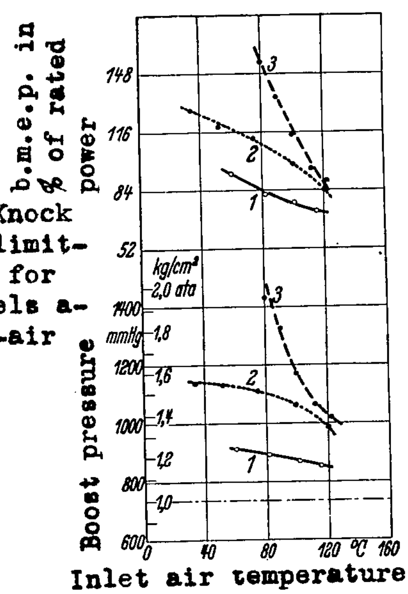


Figure 12.- Knock limitation curves for different fuels against inlet-air temperature.

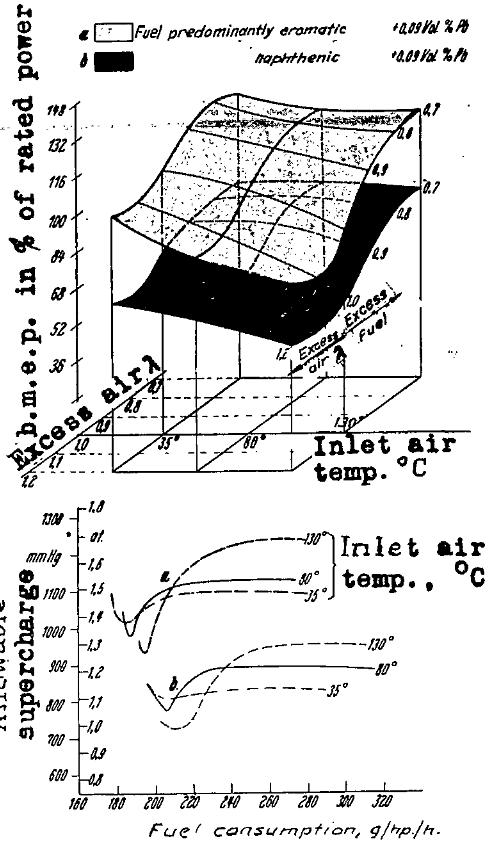


Figure 13.- Obtainable b.m.e.p. at knock boundary of two 87-octane fuels by DVL test method.

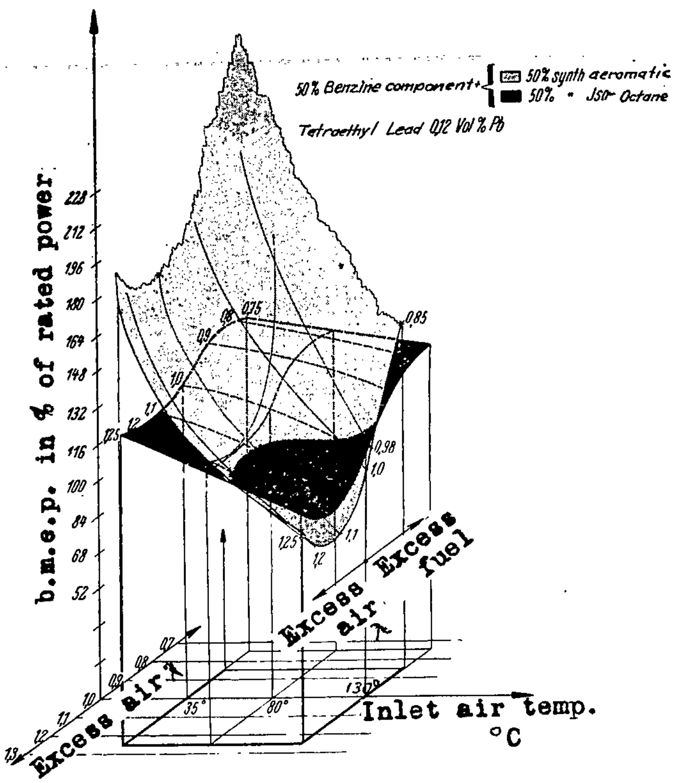


Figure 14.- Obtainable b.m.e.p. at knock boundary of two 100-octane fuels by DVL test method.

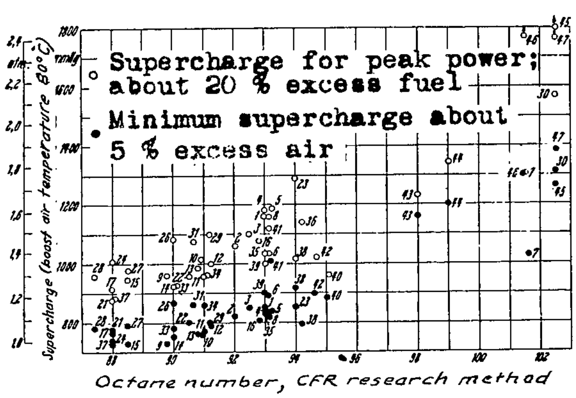


Figure 15.- Relation between CFR research octane number and boost pressure at incipient knock in the BMW-132 aero-engine, single cylinder.

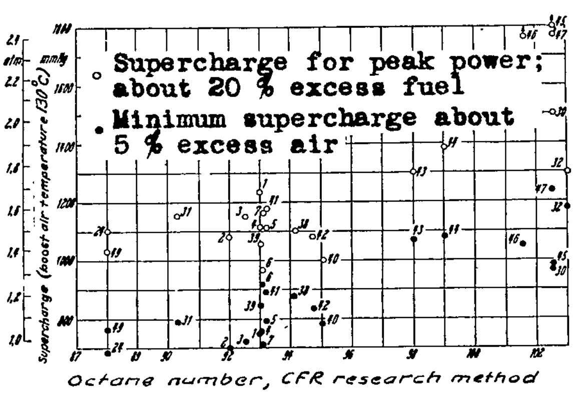


Figure 16.- Relation between CFR research octane number and boost pressure at incipient knock in the BMW-132 aero-engine, single cylinder