Chapter

37

Octane Testing

Photo . Waukesha F4 Supercharge Knock Engine with modern electronics (circa 2005)

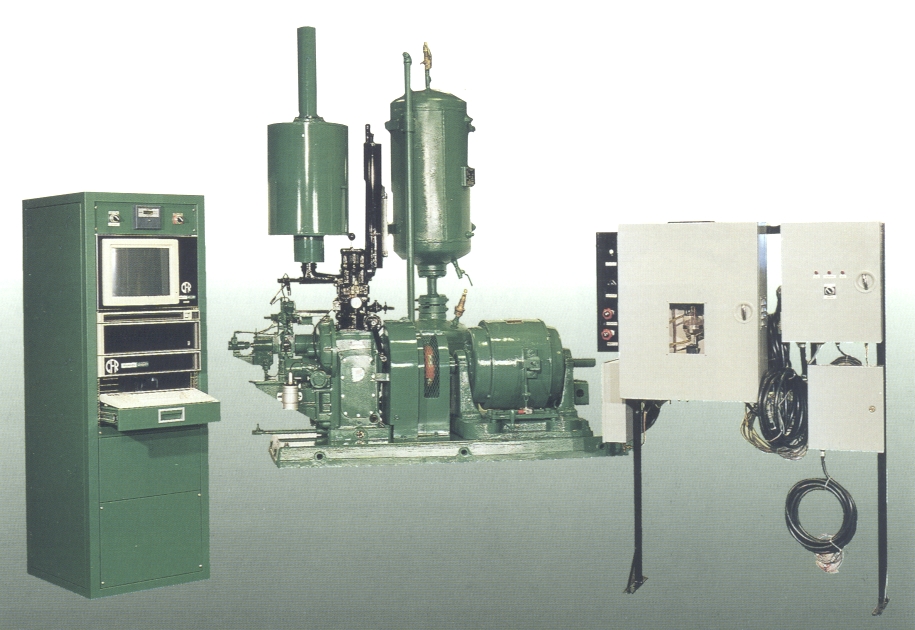


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# Summary

# Octane

The problem of engine knock is understood. Octane scale is established, and Alkyl Lead is discovered.

The fuel factor which, more than any other, tends to limit engine output is **detonation**. Other important factors are freedom from vapour lock, uniform distribution of fuel among the various cylinders, absence of a tendency to form deposits in the combustion chamber or on the spark plugs or valves. In addition, the fuel must be stable in storage, free from corrosive action on engine parts or fuel tanks and sufficiently volatile to give easy starting at low temperatures and to avoid dilution of the lubricating oil with heavy ends of the fuel.[[1]](#endnote-1)

# The Problem of Detonation

The Problem of Detonation [[2]](#endnote-2)

The importance of detonation in aircraft engine cannot be overestimated. Unlike detonation in automobile engines which result in audible knocking and harsh running of an engine, these effects are scarcely noticeable in an aircraft engine. The results of detonation, however, are far more serious, in that with the occurrence of detonation, flame temperatures during the combustion process are increased with resultant increase in temperature of working parts of the engine. If allowed to persist, detonation may cause not only lubrication failure of the piston but actually burning or fusing of the piston and/or cylinder head. Frequently, the first evidence is a major failure such as piston seizure or piston or head burning.

Engines vary in their tendency to detonate, and one important factor is the working temperature of the combustion chamber - hot valves, pistons and cylinders can pre-heat the fuel-air charge before ignition.

An equally important factor is fuel-air mixture strength, as weak mixtures have an increased tendency to detonate.

Detonation can be avoided by suitable engine design and compression ratios for a given fuel. Equally it can be avoided by using fuel of high enough anti-knock value as to meet the requirements of the engine. This led to a test engine so that comparisons could be made between fuels and a scale for making that comparison.

The cause of “Knock”

When the fuel-air charge in the cylinders is ignited by the spark, the flame travels through the combustion chamber at a speed in the order of 15 to 30 metres/sec. The gases formed by the combustion occupy considerably greater volume then the original fuel-air charge, hence the mixture ahead of the flame is progressively and rapidly compressed and, in consequence, its temperature rises. Under certain conditions this rise in temperature may be so great that the mixture ahead of the flame ignites spontaneously and an explosion wave occurs, causing the familiar “metallic” sound of detonation (knock). In severe cases of detonation, the mechanical stresses so caused may lead to fractured pistons, etc., and destruction of the engine. The general noise level in multi-cylinder engines is such that detonation is not readily detected by ear, particularly in flight, and it is obviously of great importance to ensure that detonation does not occur. Certain instruments are available for detecting detonation by other means, and have been used for testing purposes in laboratories, but they involve special fittings to be attached to each cylinder and introduce complications for flight operation.

Detonation is to a large extent controlled by the quality of the fuel, although engine factors, such as compression ratio, boost pressure, speed, air intake temperature, ignition advance and cylinder cooling also have some effect. The higher the anti-knock value of the fuel, the higher the permissible compression ratio or boost, and the greater the power that can be obtained from a given engine, provided the latter is designed to withstand the increased pressures and temperatures involved.

Early Work on Understanding “Knock”

Knocking, or detonation, was observed in motor vehicle engines early in their use, and by 1906 it was being actively investigated by Professor Bertram Hopkinson and his young assistant Harry Ricardo at Cambridge University. In early aircraft engines, knocking was thought to be a result of inadequate engine cooling. The understanding of the knock mechanism and the crucial role played by the fuel itself was to have a profound effect on both the aviation and petroleum industries.

World War I accentuated the knock problem because every program to develop more powerful engines was ultimately limited by the detonation characteristics of the fuel. Hopkinson observed in 1906 that pre-ignition and detonation were two distinct phenomena, and that the latter was responsible for the former. Pre-ignition (the tendency of fuel to ignite ahead of the spark due to the presence of localized hot spots) was later proved to be the real wrecker of lightly built aircraft engines. It had been substantially ignored because it caused no alarming noises, as did detonation.

Thus, the first known studies of detonation and overheating in aircraft engines were made by Professor A. H. Gibson in 1915 at the Royal Aircraft Factory (later the Royal Aircraft Establishment at Farnborough) UK. During full scale engine testing the combined noise of the engine and the propeller made it impossible to detect this knocking or detonation. Gibson was able to evaluate the performance by observing the extent to which air-cooled cylinders glowed red during tests at night. He found that overheating and thus detonation lessened by enriching the fuel/air ratio, and also observed the aromatic and benzol blended fuels were less susceptible to overheating. These facts were key to the British military aviation thinking in World War I when it was common practice to add Benzol (20%) to the aviation fuels imported from America to support their war effort.

# Ricardo Test Engine

Harry Ricardo's first independent work after leaving Cambridge was conducted from 1916 to 1918 on the investigation of the detonation qualities of fuels using a single cylinder supercharged engine of his own design. He compared the relative merits of aromatic, naphthenic, and paraffinic fuels by varying the boost pressure until detonation occurred. He was able to show that aromatics were the best while the straight-chain paraffins were the worst in detonation qualities. He was also able to prove Hopkinson's theory that detonation was responsible for pre-ignition. This work led the Asiatic Petroleum Company (part of the Shell Company) in 1919 to hire Ricardo to set up a research laboratory to investigate further the phenomena of detonation and its relation to fuel quality.

Photo 2. Sir Harry Ralph Ricardo



Ricardo designed a variable compression test engine and had associates Henry Tizard and David Pye investigate the chemical and thermodynamic properties of the fuels that would be run in the engine. Tizard and Pye established three important principles:

It was the work of Sir Harry Ricardo for the Shell Company which established that:

* Chemical compositions of fuels had a profound effect upon engine performance;
* At a single compression ratio, the actual differences between the fuels in terms of power development were about 4 %.
* The more detonation-resistant the fuel, the higher the compression ratio that could be obtained and therefore the more efficient and greater the power output.

The findings of Ricardo and his group appeared in 1923 in a classic report entitled: "The Internal Combustion Engine". In the report Ricardo pointed out that thephenomenon of detonation is by far the most important factor in determining the quality of a fuel, and that it depends primarily on its chemical composition.

Sir Harry best described the problem in 1923 as such:

“When the rate of temperature rise due to compression by the burning portion of the charge exceeds that at which it can get rid of its heat by conduction, convection, etc. by a certain margin, the remaining portion ignites spontaneously throughout its whole bulk, thus setting up an explosion wave which strikes the walls of the cylinder with a hammer-like blow and reacting in its turn, compresses afresh the portion first ignited. This further raises the temperature of that portion and with it the temperature and any isolated or partially insulated objects in its vicinity, thus ultimately giving rise to pre-ignition.”

Ricardo realized that in order to devise a reproducible method for rating fuels, good reference fuels would be needed. He had found that pure toluene showed the highest anti-knock quality when used as a fuel. He decided to express the detonation quality of fuels in terms of their relative toluene content. Asiatic Petroleum prepared a quantity of aromatic free reference fuel by acid treating it. Blends of this fuel with pure toluene were run in the test engine to determine the detonation point versus the percentage of toluene in each blend. Using this Toluene Rating System, the highest useful compression ratio could be established for any test engine with a given fuel. This was later superseded in the early 1930’s by the Cooperative Fuel Research engine and the “Octane scale” we have today.

# Octane Number and Its Measurement

Early attempts at measuring the anti-knock values of fuels were on the basis of the maximum compression ratio permissible with a specific degree of detonation (Highest Useful Compression Ratio, or H.U.C.R.) under specified engine conditions. Even when all possible care was taken to keep the engine conditions constant, it was found that the HUCR for a given fuel varied slightly from day to day. For this reason, it became general practice to compare the test fuel with blends of two reference fuels, one of high, the other of low anti-knock value. This practice continues today. To ensure that the reference fuels are readily reproducible, and do not change in rating through ‘weathering’ (loss of lighter component by evaporation), pure hydrocarbons were chosen.

# CFR Engine Development

Tests on multi-cylinder engines are obviously impracticable as a means of day to day control of anti-knock value of refinery production of aviation gasoline, checking tank stocks, etc. For this reason, a small single cylinder testing engine was designed as the result of co-operative work by the Cooperative Fuel Research (C.F.R.) Committee of America.

In 1921 the Cooperative Fuel Research (CFR) Committee was formed, including members of the Society of Automotive Engineers (SAE), the National Automobile Chamber of Commerce, the American Petroleum Institute (API), and the U.S. Bureau of Standards to: “*study problems involved in the mutual adaptation of the fuel and engine to each other to the end of the national economy and internal combustion engine efficiency”*.

Between 1921, when the CFR was organized, and 1926, nearly all of the major oil companies and several universities had set up knock testing laboratories. During 1926, the CFR requested that the Bureau of Standards make a survey of the methods for measuring the anti-knock qualities of fuels. It was found that there was very little common ground, and almost no correlation among various laboratories. Many different engines were in use, and although repeatability was possible on the same engine in one laboratory, results were almost impossible to duplicate by others, due to differences in operating conditions. This problem was compounded by the lack of suitable reference fuels; however, this problem was to be solved by Dr. Graham Edgar.

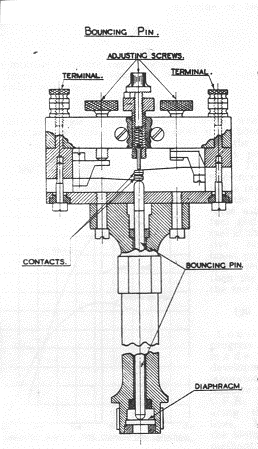
By 1932, industry had generally adopted a standardized method for knock rating, using an engine designed by H. L. Horning of the Waukesha Motor Company for the CFR Committee, and Edgar's fuel standards.

CFR Engine

The CFR Engine is a liquid cooled single cylinder engine of bore 3 ¼ inches and stroke of 4 ½ inches. It is of rugged construction and is designed so that engine conditions can be closely controlled. The compression ratio is infinitely variable between 3:1 and 30:1, although the normal working range is from 4:1 to 10:1.

The classic “Bouncing Pin” - To diminish personal error of detecting ‘knock’, detonation is detected by an instrument known as the bouncing pin. (Fig. 1.) The cylinder head of the engine is provided with a hole similar to that in which a spark plug is screwed, but at the opposite side of the combustion chamber i.e. approximately at the point where detonation occurs. The bouncing pin is screwed into this hole.

Figure . CFR Octane Engine ‘Bouncing Pin’



At its lower end is a thin steel diaphragm, above which rests a light metal rod, on top of which presses a leaf spring. Immediately above this spring is a second leaf spring. The two springs are provided electrical contacts, the springs being adjusted so that these contacts are a few thousandths of an inch apart. The two contacts form part of an electrical circuit. When no detonation occurs, no current flows through the circuit.

When detonation is sufficiently intense, the resulting increase in pressure causes the diaphragm to throw the pin against the lower spring, thus closing the circuit, the amount of current flowing increasing with intensity of detonation. The amount of current is indicated by means of a ‘knock- meter’, which consists of a hot wire ammeter.

The only change in engine design has been the modification of the electrical systems replacing them with modern electronics components, apart from this upgrade the CFR engine has essentially remained unchanged since its introduction in 1932.

# ASTM Motor Method (F-2)

The test is carried out by adjusting the compression ratio so that a specified intensity of detention is obtained using the test fuel. Two reference blends, one of slightly higher, and one of slightly lower anti-knock value than the test fuel, are compared with the latter and the matching reference fuel blend determined by interpolation of knock-meter readings. Since engine conditions affect not only the absolute but also their relative ratings of different fuels, they must be rigidly controlled. The conditions employed were devised so that the ratings obtained correlated with those determined in motor cars on the road; the method is therefore sometimes known as the Motor Method. The principal conditions, which were also used in testing aviation gasolines, are given in Table 1.

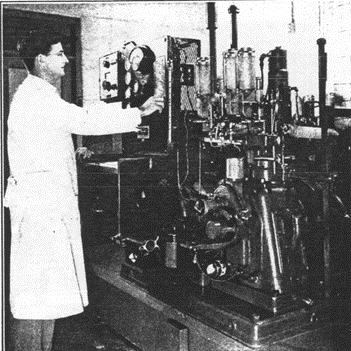
Table . Motor Method engine test conditions.

|  |  |
| --- | --- |
| Speed | 900 rpm |
| Jacket Temperature | 212 deg. F. (100 deg. C.) |
| Inlet air temperature | Atmospheric |
| Mixture temperature | 300 deg. F. (149 deg. C.) |
| Mixture Strength | For maximum knock |
| Spark advance | Automatically varied with compression ratio, 26 degrees E (Before Top Dead Centre) at 5:1 |

This method was adopted by the American Society for Testing Materials (ASTM) around 1933. The ASTM Designation was D357-34T – which indicates that in 1934 the method was still considered Tentative. For fuels rating above 100 octane number, the Institute of Petroleum (UK) standardised a modified form of this test, in which a constant spark advance of 17 degrees E was specified.

Since fuels of higher knock rating than iso-octane can be produced, various methods of extending the octane scale have been used. Results can be expressed in terms of cc (milli-litres) of Tetra Ethyl Lead per gallon (or litre) of iso-octane, or by an extrapolation of the octane scale. The method adopted by the Institute of Petroleum was to calculate blends of two secondary reference fuels, each containing 4 cc TEL per Imperial gallon, and to extrapolate the calibration curve beyond 100 Octane Number.

Photo 3. CFR Engine circa 1940.



Note the operator is looking at the “knock-meter”, and the 3 fuel chambers - one each for the test fuel and the two reference fuels.

# CFR 1-C Aviation Method

Another method developed specifically for aviation gasolines was the CFR 1-C Method. The engine used is a slightly modified form of the CFR engine. Knock intensity is measured not by the bouncing pin, but by a thermal plug, which is, in fact, a thermocouple designed to screw into the bouncing pin hole. Thus, this method was based on the temperature rise, rather than on the rate of pressure rise, incident on detonation. The principal engine conditions for this method are given in Table 2.

Table . CFR 1-C Aviation Method engine test conditions.

|  |  |
| --- | --- |
| Speed | 1,200 rpm |
| Jacket Temperature | 374 deg. F. (190 deg. C.) |
| Inlet air temperature | 125 deg. F. (~52 deg. C.) |
| Mixture temperature | 220 deg. F. (100 deg. C.) |
| Mixture Strength | For maximum thermal plug temperature |
| Spark advance | 35 degrees E |

Around the late 1960’s and early 1970’s this method was replaced in most specifications by the adoption of the Motor Method.

# U.S. Army Method Engine Test

Yet another similar method was that developed by the U.S. Army and was incorporated in their fuel specifications from about the early 1930’s. It was similar in operation to the Motor Method and 1-C Aviation Method and used thermal plug measurement, but there were some differences in engine size for example the bore was 2 ⅝ inches compared to 3 ¼ inches for the CFR engine. Refer to Table 3.

Table . US Army Method engine test conditions for aviation fuels.

|  |  |
| --- | --- |
| Speed | 1,200 rpm |
| Jacket Temperature | 330 deg. F. (~166 deg. C.) |
| Inlet air temperature | Atmospheric |
| Mixture temperature | No heat |
| Mixture Strength | For maximum knock |
| Spark advance | 30 degrees E (Before Top Dead Centre) |

In the United States of 1940 both the ASTM Motor Method and U.S. Army Method were used, however with the aviation fuel requirements (and thus testing) of the combined Allied Air Forces increasing dramatically in World War II, the U.S. Army method was to quickly become replaced by the ASTM Motor Method.

# Rating Aviation Fuels in Full-Scale Aircraft Engines[[3]](#endnote-3)

Origin of CFR Aviation Gasoline Detonation Tests

The first step leading to the formation of the Aviation-Gasoline Detonation (A.G.D.) Sub-Committee of the Cooperative Research Committee was a resolution adopted by the Fuels and Lubricant Division of the Aeronautical Chamber of Commerce of America at its meeting in Cleveland, Ohio on September 4, 1931. This resolution, directed to the CFR Committee asked that the Aeronautical Chamber be permitted to join with the committee in extending the C.F.R. Committee’s research on the measurement of detonation to specifically include aviation fuels and aircraft engines. While the resolution was favourably received by the CFR Committee, the lack of financing delayed work until May 1933 when a detailed test procedure was worked out by the special program sub-committee from then on, to be known as the A.G.D. Steering Committee.

Objectives of the Test Program

The principal purpose of this series of tests was to ascertain whether octane number determinations made by the CFR Motor Method (ASTM D357-34T) of rating motor fuels correlated satisfactorily with the behaviour of aviation fuels of widely different types in representative full-scale aircraft engines; and, if necessary, to develop a method of knock rating of aviation gasolines which will be applicable specifically to all varieties of fuels and to all types of spark ignition engines.

The program provided for the investigation of three series of fuels:

* Those whose knock characteristics were essentially unchanged under varying test conditions.
* Those whose knock rating decreased with increasing severity of test conditions.
* Those whose knock rating improved with increasing severity of test conditions.

Participants of A.G.D. Sub-Committee

Participants were to include any organisation willing to contribute laboratory facilities, test or reference fuels, or cash donations, and to cooperate actively in carrying out the program. Accordingly, invitations were extended to the leading aircraft engine builders, the Materiel Division of the (U.S.) Army Air Corps, the Bureau of Aeronautics of the (U.S.) Navy Department, the (U.S.) National Bureau of Standards, and the suppliers of aviation gasoline. Later the Canadian National Research Council also joined the program.

**Oil Companies and their representatives**

The Barrett Co. S.P. Miller

Continental Oil Co. B.E. Sibley

Phillips Petroleum Co. G.G. Oberfell

Shell Refining Co. T.B. Rendel

Sinclair Refining Co. G.R. Lord

Socony-Vacuum Oil Co., Inc. C.H. Schlesman

**Stanavo Specification Board**

Standard Oil CO. (Indiana) D.P. Barnard

Standard Oil Co. (California) J.B. Terry

Standard Oil Development Co. A.E. Becker

The Texas Co. G.W. Gray

**Other participants**

Ethyl Gasoline Corp. Graham Edgar & Samuel D. Heron

General Motors Corp. T.A. Boyd

National Bureau of Standards H.C. Dickinson

National Research Council of Canada J.H. Parkin

Society of Automotive Engineers, Inc. C.B. Veal (Secretary)

U.S. Army Air Corps F.D. Klein

U.S. Navy, Bureau of Aeronautics C.F. Coe

Waukesha Motor Co. H.L. Horning

**Aircraft Engine Manufacturers**

Lycoming Manufacturing Co. V. Cronstedt

Pratt & Whitney Aircraft Co. W.A. Parkins

Wright Aeronautical Corp. Arthur Nutt (Chairman)

This sub-committee contained some of the most noted researchers in the US, including Sam Heron and Frank Klein who were involved in the US Army Air Corps testing on Avgas 100; Graham Edgar who established the Octane Scale; Thomas Boyd who with Midgley, had discovered the anti-knock additive Tetra Ethyl Lead.

Fuels & Engines Used During Tests

There were three reference fuels of 73, 80 and 87 octane number, designated as No. 1, No. 2 and No. 3, respectively – No. 1 being a blend of Standard Oil Development Company’s reference fuels A-3 and C-7 (later listed as C-6); and the other two were C-7 (or C-6), and C-7 (or C-6) plus tetraethyl lead. The test fuels were based on the three distinct types previously described; treating each test gasoline with tetraethyl lead and blending straight run gasoline with benzol gave four groups of test fuels – a total of 23 test fuels.

a-type plus lead (from none to 1.03 ml/L TEL) (a-4 to a-9)

a-type plus benzol (from none to 79%) (a-10 to a-14)

b-type plus lead (from none to 1.58 ml/L TEL) (b-15 to b-19)

c-type plus lead (from none to 1.43 ml/L TEL) (c-20 to c-26)

The engines used in the test work were:

* Wright Super-Conqueror SV-1570 Engine 6.5:1 compression ratio, 10:1 blower ratio, 250 deg. F. jacket temperature.
* Pratt & Whitney Hornet R-1690D Engine 6.5:1 compression ratio, 12:1 and 10:1 blower ratio.
* Lycoming R680-2 Aviation engine, 6.5:1 compression ratio, un-supercharged.
* Pratt & Whitney R-1345 Engine 6:1 compression ratio, 10:1 blower ratio.

The test fuels were markedly different in distillation, density, and octane and lead susceptibility. The test fuel a-4 is the same as fuel a-9 except for the addition of TEL, similarly test fuel b-15 is the same as b-19 except for TEL content; and c-20 the same fuel as c-26 except for TEL content. A summary of the properties is shown in Table 4.

Graph 1. Distillation Curves of Test Fuels for Full-Scale Engine Test CFR-AGD 1935

Table . Summary of data of Test Fuels for Full-Scale Engine Tests CFR-AGD 1935

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Test Fuel | a-4 | a-9 | b-15 | b-19 | c-20 | c-26 |
| MON | 73.4 | 89.6 | 68.8 | 83.0 | 69.4 | 87.1 |
| US Army Method | 73 | 94 | 69 | 86 | 69 | 90 |
| TEL (ml/L) | 0.00 | 1.03 | 0.00 | 1.58 | 0.04 | 1.43 |
| Distillation (deg. C.) | Fuel a-4 = a-9 | | Fuel b-15 = b-19 | | Fuel c-20 = c-26 | |
| Initial Boiling Point | 43 | | 51 | | 43 | |
| 10% | 71 | | 68 | | 56 | |
| 50% | 99 | | 88 | | 71 | |
| 90% | 125 | | 116 | | 95 | |
| Final Boiling Point | 163 | | 152 | | 124 | |
| Density | 0.731 | | 0.720 | | 0.689 | |
| Reid Vapour Pressure psi | 5.7 | | 5.0 | | 7.7 | |

Summary of Results and Conclusions

The tests showed satisfactory correlation (up to 87 octane number) between the Motor Method laboratory ratings for fuels and full-scale engine for those fuels (a -type) - whose knock characteristics were essentially unchanged under varying test conditions (tested with and without lead).

Similar results were obtained with those fuels (b-type) whose knock rating decreased with increasing severity of test conditions (tested with and without lead).

However, those (a-type) fuels plus benzol and those (c-type) fuels plus lead, were somewhat overrated by the laboratory Motor Method, and that performance of a particular benzol blend varied within rather wide limits – depending on engine design and operating conditions. The final conclusion was: *“in view of these results and the need of considering fuels in the range above 87 octane number, no attempt will be made to secure improved correlation by modifying the Motor Method until further experimental data is available”.*

Postscript: - This project highlighted the difficulty of using one laboratory test engine (un-supercharged) to assess a fuel at one fuel/air mix, when the actual requirements were for a fuel to be assesses at varying fuel/air mixture and varying supercharged conditions. This would be further exacerbated with higher octane fuels and high performance engines, in particularly the British liquid cooled in-line engines which had been developed on fuels with significant aromatic content (refer to the fuel used by the British in the Schneider Trophy wins). This was to be overcome with the development of a new laboratory test engine and method; CFR F-4 Supercharge Method.

It also highlighted the difference between the CFR Motor Method and the U.S. Army Air Corps Method AS3556 – the latter was to lose favour and became superceded by the CFR Motor Method.

# British View

E.L. Bass of the Shell Company in the UK presented a paper in Paris at the Chambre Syndicale des Industries Aéronautiques on the 25th November 1936 titled ‘High Octane Fuels’. He discussed some of the changes in engine design, the use of high octane fuels in civil aviation, the (knock) engine testing of high anti-knock fuels and the discrepancies in the methods.

In late 1936, Bass stated that:

‘The CFR engine is now almost universally employed for the testing of aviation fuels. The modified motor method of operating the CFR was first adopted by the British Air Ministry for aviation fuels as a result of correlation work carried out in 1933. This method has now been adopted by various European Governments, but in America the standard motor method of operating the CFR has been adopted for all civil aviation fuels as a result of the tests made by the CFR Aviation Knock-Rating Committee (May 1936). The International Air Traffic Association has also adopted the CFR motor method for its fuel specifications’.

He then went on to state that there was very little difference between the modified motor method and standard motor method, however the U.S. Army method was markedly different both in engine and method. Further, in his view for fuels greater than 87 octane, the CFR motor method (standard or modified) in its present form was totally unsuited for testing of aviation fuels. He described the problems as:

(a) the use of the bouncing pin as a means of measuring detonation at the high compression ratios which were necessary when testing fuels of 87 octane and greater.

(b) The fuel system and carburettor of the CFR engine were inadequate to determine exactly the influence of mixture strength on knock rating.

(c) It is an open question as to whether it is correct to use n-Heptane and Iso-octane as the reference fuels for the CFR engine. Blends of these fuels vary in many respected from the actual fuels which are used for aircraft engines.

Thus, an unnecessary variable is introduced which could be avoided if some such standard as H.U.C.R. (Highest Useful Compression Ratio), or allowable boost ratio were used. In other respects, the CFR engine had proved itself a reliable and sturdy unit for laboratory service, so that it seems that in the first place, other means of detecting detonation must be employed, and a new design of carburettor with flow meters attached to enable the engine to run with any desired fuel/air ratio.

[Comment. It should be noted that H.U.C.R. and the Toluene Rating scale were developed by Ricardo with his E35 variable compression engine. Both Bass and Ricardo worked for the Shell Company.]

It should be remembered that the purpose of these laboratory engine tests was to predict fuel performance of fuels when used in full scale engines.

The correlation work carried out by the British Air Ministry by David R. Pye was done exclusively on single cylinder engines, general experience having shown that the results obtained on single cylinder units could be applied to the main engines.

Photo 4. David R. Pye (1952)[[4]](#endnote-4)



In America, the use of single cylinder engines for this purpose was regarded with disfavour, and full- scale multi-cylinder engines were used for all the correlation work done by the CFR Committee.

Regardless of whichever school of thought was correct, certain problems were common to both and had not been satisfactorily been solved (by 1936). The means of detecting detonation and the degree of detonation which can be tolerated must be exactly defined. The aural method was used on the British single cylinder engines, the temperature measurement method (thermal plug) was used for the American CFR series of engine tests. The Europeans found the thermal plug method too insensitive and retained with the aural method since a skilled operator could detect the detonation before the increase in temperatures of the cylinder barrel or head as recorded by the thermocouple. Bass suggested a delicate indicator to respond to the pressure wave of the detonation – this would become the ‘knock meter’. Bass reported that within recent years (circa 1936), the electric indicator employing a pressure unit coupled through the necessary amplifying valves to a cathode ray tube, has been the subject of considerable development work.

In his conclusions Bass stated, the rating of fuels of 100 octane number demands immediate investigation. The CFR engine as it stands at present, when operated under motor method or modified motor method conditions, is totally unsuited for this purpose, and fresh correlation work on high octane fuels will need to be carried out concurrently with the development of operating the CFR engine. This will involve:

(a) Investigation into other methods of detecting detonation, both on full-scale engines and the laboratory fuel-testing unit. For this purpose, the electric indicator appears to be the most suitable apparatus.

(b) Fuels will have to be rated at least two mixture strengths. i.e., equivalent to cruising and take-off conditions, unless it can be shown by experiment that all fuels will have the same relative rating over the range of mixture strengths involved.

This would lead to the development of the CFR F-4 Supercharge engine test.

# Mixture response & the need for a new test

In the early 1940’s with the development of high performance fighter aircraft with supercharged engines such as the Spitfire and others, it became apparent that no single test could accurately predict the anti-knock performance of fuels under various operating conditions prevailing in service aircraft. Under cruising conditions, a low fuel consumption is required, and hence relatively weak mixtures are used to extend the range of the aircraft. However, during take-off, the engine should develop the maximum power possible, and rich mixtures are used, since these permit higher boost pressures and therefore greater power output before detonation occurs. Two fuels may have the same anti-knock values at weak mixtures but different anti-knock values at rich mixtures. This problem was highlighted more in liquid cooled aircraft engines favoured by the British than in the air-cooled radial engines used by the Americans.

Rich Mixture Rating

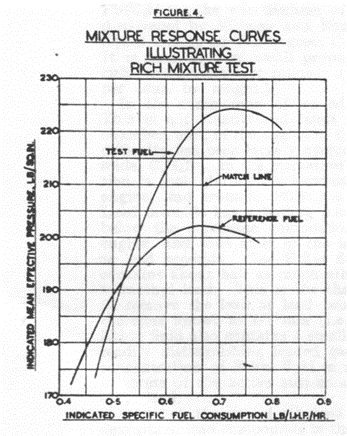
CFR - F4 Supercharged Engine

As neither the Motor Method nor the 1-C Aviation Method gave a satisfactory measure of the anti-knock performance of fuels as rich mixtures, a method was developed for determining rich mixture ratings of fuels. It had been known for some time that the relative knock ratings of fuels depended on the boost pressure, hence the method chosen was based on constant compression ratio and variable boost pressure rather than on variable compression ratio as in the Motor Method or 1-C Aviation Methods. Furthermore, the method was based on a supercharged engine which was obviously more in line with actual aircraft engines in use.

The engine chosen was a modified form of the CFR engine with operating conditions giving the best correlation with rich mixture ratings in full scale engines.

The fuel is injected into the air intake pipe before the mixture heater, instead of being vapourised in a carburettor as in the Motor and 1-C Methods. A mixture response curve is plotted using the power output in terms of brake or indicated horse-power or mean effective pressure (I.M.E.P.) determined over a sufficient range of mixture strength to establish the position of the peak of the curve, the power output I.M.E.P. (Indicated Mean Effective Pressure) is plotted against specific fuel consumptions or fuel-air ratios. Similar curves are prepared using reference fuels and by using interpolation at the peaks of the curves the Rich Mixture Rating is determined.

Figure 2. Mixture Response Curves for CFR Supercharged Engine.



Edgar sets the ‘Octane Number Scale’

A significant milestone in aviation fuels research was reached during 1927, when following an extensive study of the detonation characteristics of pure hydrocarbons, Dr. Graham Edgar of the Ethyl Gasoline Corporation, proposed the adoption of two pure paraffin hydrocarbons as reference fuels for knock rating. Edgar found that normal Heptane (C7H16), would detonate almost under any condition and he selected it as Zero on his 0-100 Octane rating scale. He also found that Iso-octane specifically 2,2,4 Trimethyl pentane had the highest knock resistance higher than any gasoline, and this became 100 on the rating scale. Furthermore, they were almost identical in volatility and chemical properties, particularly boiling point; refer to Table 5. Edgar demonstrated that the two fuels could be blended together to duplicate the knocking characteristics of any known motor fuels. A fuel, which has the same anti-knock value as a blend of, say 80% (by volume) Iso-octane and 20% (by volume) n-Heptane is said to have an “octane number” of 80. Thus, began the Octane Number scale, which is still the standard method for quoting the anti-knock quality of gasoline.

Iso-octane is made by chemical synthesis. Normal Heptane was originally obtained from the sap of the Jeffrey pine tree, by distillation and subsequent purification, but now it is made by synthetic methods. During World War II, pure Iso-octane and normal Heptane were too expensive to be used in routine tests, and secondary reference fuels were used. The latter included a commercial grade of Iso-octane, straight run gasolines of high and low octanes and the blends of these with Tetra Ethyl Lead. Secondary reference fuels were usually prepared in large batches so that all laboratories used the same material, and each batch was calibrated against the primary reference fuels. In the case of full-scale single cylinder and multi-cylinder engine tests, a typical 100 octane gasoline was often used.

Table . Properties of Reference fuels normal Heptane and 2,2,4 Trimethyl Pentane (‘Iso-Octane’).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Compound | Molecular weight | Freezing point deg. C. | Boiling point deg. C. | Density | CAS No. |
| n-Heptane | 100.20 | -90.6 | 98.5 | 0.6837 | 142-82-5 |
| 2,2,4-Trimethyl Pentane | 114.23 | -107.3 | 99.2 | 0.6877 | 540-84-1 |

Initial Testing of Leaded Aviation Fuel

In 1922 at McCook Field, the US Army Air Service began testing gasoline containing TEL (Lead), but encountered problems with lead oxide deposits on spark plugs, exhaust valves and pistons. These tests were discontinued pending the development of a suitable scavenging agent to minimise these deposits.

The US Navy in 1927 first began testing leaded gasolines in its new 410 HP Pratt & Whitney Wasp engines; the spark plug fouling problem having been solved by the addition of Ethylene Dibromide as a scavenging agent. They carried cans of TEL fluid in the aircraft and added it to the tanks when refuelling. This hazardous procedure continued until 1933. The work of Sam Heron, Klein and others at McCook Field, Ohio would change all this.

Perhaps the words of Sam Heron best describe the challenges in testing this new anti-knock additive in 1925 [[5]](#endnote-5) “While at McCook Field, I (Sam Heron) watched my first tests of leaded fuel with some interest. These were conducted in a Liberty cylinder using tungsten steel valves. For these tests, 16 cc of lead per gallon was used. This was based on the idea that we must be able to hop-up the worst available gasoline in the country so that it became usable in the existing engines. Carbon tetrachloride was used as a scavenger. I had never seen such awful looking exhaust valves as those which resulted from the tests with the above fuel mixture in a single-cylinder Liberty engine. The valves looked as though they had been dipped in molten slag. We were later to find out that leaded fuel is very deleterious to tungsten steel valves, even when the lead is used at a reasonable concentration and the fuel contains ethylene dibromide as a scavenger. As I remember it, I wrote from McCook Field to Dr. Graham Edgar giving details of tests conducted with leaded fuels on two different engines. This letter described tests on naturally aspirated engines and reported the power developed with leaded and unleaded fuel. This was quite a useless piece of work since the engines were not supercharged. We now know we could not expect to get any more power out of leaded fuel if the engine power was not knock limited on unleaded fuel.” The compression ratio of the engine was a low 5.35, high compression engines were still some way off. Further comparative engine tests were conducted at McCook Field using a single cylinder engine comparing Tetra Ethyl Lead in gasoline (3 cc of Ethyl lead mixture (60% lead) per US Gallon), and TEL (3 cc/USG) in gasoline plus 20% benzol, against straight aviation gasoline. There were a number of spark plug problems with the single cylinder engine tests. Tests were also conducted on a 400 HP, 9-cylinder air cooled radial engine; no trouble with spark plug deposits was experienced, but deposits were shown up on the exhaust valves, but no evidence that this caused any trouble.

[Author’s note: 16 cc/USG is an extraordinarily high lead level, approximately 4 cc TEL/Litre whereas the maximum specification for Avgas 1000 was later to be around 1.2 cc TEL/Litre, the McCook tests were conducted at nearly four times the normal maximum level of TEL].

# 1933 The CFR Knock test engine is standardized.

With suitable reference fuels now established, it took the Cooperative Fuel Research Committee to specify a suitable test engine. Because by 1933 there were at least 5 different engine tests (four of which used the Octane scale).

Table 6. Comparison of knock test engines.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1933 | CFR | CFR | Armstrong-Whitworth | Ethyl Engine | US Army | Ricardo | CFR | CFR |
| Introduced | 1929? | 1929? | 1933 | 1931? | 1933? | 1919 | 1931 | 1942 |
|  | CFR | CFR | BP |  | Spec. Y-3557-F | Shell |  |  |
| Type | Research RON | Motor MON |  | S30 | S30 | E35 | Aviation Lean Rating | Supercharge Rich rating |
| ASTM Designation | F1 | F2 |  |  |  |  | F3 | F4 |
| ASTM Method | D2699 | D357-34T D2700 |  |  |  |  | D614 then D2700 in 1968 | D909 |
| IP Method |  | IP44/55 |  |  |  |  | IP42/55 | IP119/81 |
| Engine speed rpm | 600 | 900 | 750 | 600 | 900 |  | 900 | 1,800 |
| Compression | Variable | Variable | Variable | Fixed | Fixed | Variable | Variable | Fixed 7.0 to 1 |
| Engine Cooling Jacket Temp. Deg. C | 100 |  | 50 | 150 | 190 | 60 | 100 | 190 |
| Results | Octane scale | Octane scale. measured by bouncing pin | Octane scale | Octane scale | Octane scale measured by thermal plug | HUCR \*  poor correlation to Octane scale. Similar to aero piston speed | Octane scale | PN  Performance Number |

\* HUCR = Highest Useful Compression Ratio

By 1932 most oil companies had adopted a standardized method for operating the CFR engine for octane ratings.

# Engine Test Methods[[6]](#endnote-6)

In the early 1930’s, the Cooperative Fuel Research Council of the Society of Automotive Engineers introduced the CFR test engine and developed a test method and rating scale which expressed the anti-knock properties of fuels in terms of an octane number.

These methods were subsequently developed into ASTM methods (American Society for Testing Materials) for the U.S., and also equivalent IP (Institute of Petroleum) in the U.K. Other countries around the world would adopt one of these systems. From time to time these methods are revised and updated.

While in the 1930’s there was a drive to standardise the octane test engine, there was still variation between countries. As of 1938 there were three methods used in evaluating the octane number of aviation gasolines – the British Air Ministry Method (B.A.M.), the U.S. Army Method and the ASTM (CFR) Motor Method. These methods were designed in an attempt to correlate laboratory anti-knock ratings of fuels with their performance in full scale aircraft engines. The Americans favoured air-cooled radial engines, and the U.S. Army Test Method gave a closer correlation with American engines. While the British favoured inline engines and aromatic blends - perhaps a legacy from the days of the Schneider Trophy races; for these the B.A.M. method gave a better correlation. The ASTM method was a good compromise for rating all types of fuels and was considered a reliable criterion. Table 6. highlights the differences in these engine test methods which were all based on the Waukesha engine.

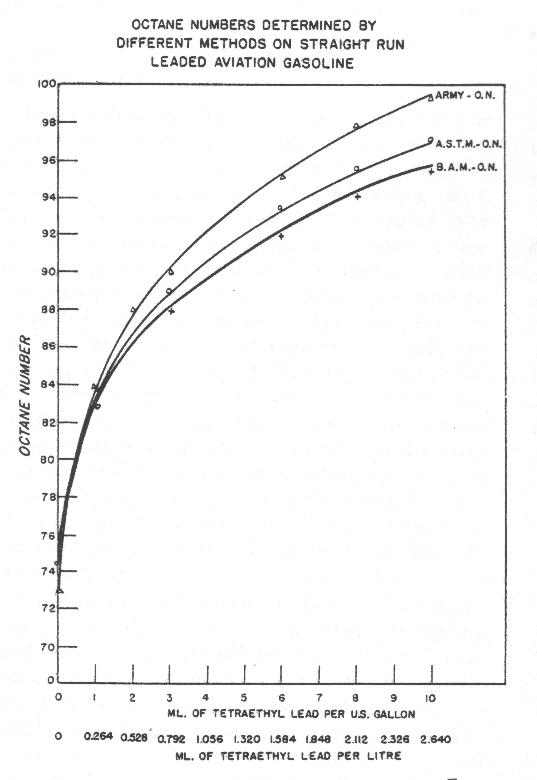
Table 7. Comparison of Knock Testing Methods[[7]](#endnote-7)

|  |  |  |  |
| --- | --- | --- | --- |
| Method | British Air Ministry | U.S. Army Method | A.S.T.M. (CFR) Motor |
| Engine | Waukesha | Waukesha | Waukesha |
| Cylinder diameter inches (mm) | 3 ¼ (82.5 mm) | 2 5/8 (66.7 mm) | 3 ¼ (82.5 mm) |
| Intake Valve | Plain | Plain | Shrouded |
| Speed RPM | 900 | 1200 | 900 |
| Jacket Temp. deg. F. | 212 (100 deg. C.) | 300 (149 deg. C.) | 212 (100 deg. C.) |
| Manifold Heat deg. F. | 260 (127 deg. C.) | None | 300 (149 deg. C.) |
| Spark Advance | 26 (at 5:1 Compression) | 30 (Constant) | 26 (at 5:1 Compression) |
| Mixture Ratio | Max. knock | Max. knock | Max. knock |
| Knock Detector | Bouncing Pin | Temp. Plug | Bouncing Pin |

The consequences of different methods were to result in slightly different specifications for aviation gasolines depending on the customer, however many of the suppliers for economic reasons produced aviation gasolines which would meet the most stringent parameter of any of these specifications, and thus ensuring meet them all. The following chart shows the results of measuring the same fuel by different methods.

The octane number of certain fuels in comparison with the standard primary reference fuels (iso-octane and normal heptane) varies somewhat depending on the test method used. Figure 4. gives the curves illustrating the relative anti-knock value, determined by the three methods.

Figure 3. Octane numbers by different methods



This variation in octane due to engine test method and addition of lead was noticed with individual blendstocks.

The following table compares various blendstocks in use in 1938 and the effect of lead on octane rating when tested by British Air Ministry (B.A.M.), U.S. Army, and A.S.T.M (CFR) methods

Table 8. Effect of Test Method on Octane Number.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Blendstock | Lead Level cc/USG (ml/Litre) | B.A.M. | US Army | A.S.T.M. (CFR) |
| Catalytically Cracked Gasoline | Clear | 78.0 | 75.5 | 77.7 |
| Catalytically Cracked Gasoline | 3.0 (0.792) | 92.0 | 93.1 | 91.0 |
| Aromatic Blend | Clear | 78.4 | 76.3 | 77.6 |
| Aromatic Blend | 3.0 (0.792) | 90.5 | 92.7 | 89.2 |
| Straight Run Naphtha | Clear | 75.4 | 72.8 | 74.1 |
| Straight Run Naphtha | 3.0 (0.792) | 88.2 | 90.2 | 88.6 |
| Hydrogenated Naphtha | Clear | 77.6 | 75.8 | 76.0 |
| Hydrogenated Naphtha | 3.0 (0.792) | 90.1 | 92.5 | 90.0 |
| Commercial Iso-Octane Blend | Clear | - | 84.5 | 83.0 |
| Commercial Iso-Octane Blend | 3.0 (0.792) | - | 100.0 | 96.0 |
| Iso-Propyl Ether Blend | Clear | - | 85.1 | 83.0 |
| Iso-Propyl Ether Blend | 3.0 (0.792) | - | 100+ | 100+ |

The Second World War would see the further rationalisation of existing engine test methods and the development of new engine test methods to measure different performance parameters. The knock rating test engines were also used for determining the octane of motor gasolines and while the test method is now standardised, progress continues even today with the refinement in instrumentation of the engine.

The engine test methods applied to motor gasolines and aviation gasolines. For completeness both are listed below. The data is from 1961 and many of the methods have been revise in the last 50 years, however the data below gives some history of the methods and the transition from the CFR methods.

Motor Gasoline Test Methods

Two different methods of test are necessary to enable the road performance of a motor gasoline to be predicted, as there are numerous designs of engines operating under various load-speed-temperature conditions. These tests cover the extremes of automobile engine operations, the severe test being known as the Motor Method, and the moderate test as the Research Method.

Motor Method (MON)

The full designation of this method is: - Standard Method of Test for Knock Characteristics of Motor Fuels by the Motor Method.

IP designation: - IP44/55 (the latter designation indicates the year the method was adopted).

ASTM designation: - ASTM D357-56

In 1968, the test method was superceded by ASTM D2700 and later its international equivalent ISO 5163.

Research Method (RON)

The full designation of this method is: - Standard Method of Test for Knock Characteristics of Motor Fuels by the Research Method.

IP designation: - IP126/55

ASTM designation: - ASTM D908-56

In 1968, this test method was superceded by ASTM D2699 and later its international equivalent ISO 5164.

Aviation Gasoline Test Methods

A piston engine in an aircraft operates at widely different air/fuel ratios, the mixture being very rich for take-off and emergency full throttle operation, and very weak mixture for economical cruising conditions. Consequently, a single test cannot predict the knocking tendency of a fuel for use in an aircraft engine and two types of test, known as Weak or Lean Mixture, and Rich Mixture tests, respectively, are normally required.

**Weak Mixture Methods**

Aviation Method (F-3)

The full designation of this method is: - Tentative Standard Method of Test for Knock Characteristics of Aviation Fuels by the Aviation Method.

IP designation: - IP42/55T (the designation ‘T’ indicates that the method is tentative).

ASTM designation: - ASTM D614-56T

The test was previously known as CRC F-3-645, but by 1961 this designation was obsolete.

Motor Method (F-2)

The procedure described above for motor gasolines test methods is used without modification for fuels which have octane numbers up to 100.

Photo 5. Waukesha F-2 Motor Octane Method (MON) Engine[[8]](#endnote-8) circa 2005



Extended Motor Method

The full designation of this method is: - Knock Rating of High Performance Fuels. Extended Motor Method.

IP designation: - IP150/55T

This method is similar to the Motor Method but is used for fuels which have octane numbers above 100.

**Rich Mixture Method**

Supercharge Method (F-4)

The full designation of this method is: - Tentative Method of Test for Knock Characteristics of Aviation Fuels by the Supercharge Method.

IP designation: - IP119/55T

ASTM designation: - ASTM D909-49T

The test was previously known as CRC F-4-443, but by 1961 this designation was obsolete. ASTM D909-58 was adopted in 1958.

The engine operating conditions for the above tests are summarised in Table 8.

Table 9. Octane Engine Test Method Conditions

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Property | Motor Method | Research Method | Aviation Method | Supercharge Method |
| Engine Speed, RPM | 900 | 600 | 1,200 | 1,800 |
| Ignition Advance O BTDC (Note 1.) | Variable | 13 | 35 | 45 |
| Air Inlet Temp. (deg. F) | 100 | Varies with barometric pressure | 125 | 225 |
| Mixture Temp. (deg. F) | 300 |  | 220 |  |
| Coolant Temp. (deg. F) | 212 | 212 | 374 | 375 |
| Compression Ratio | Varied to give standard knock intensity | | Varied to give max. thermal-plug temp. |  |
| Detonation-Intensity indication | Detonation meter pickup (pressure) | | Thermal plug temp. | Aural Assessment of light knock |

Note 1. O BTDC = degrees of ignition advance before top dead centre piston position.

Methods of knock assessment have been many and varied. Until 1954, the accepted instrument for the measurement of knock in the Research and Motor Methods was the bouncing pin (Refer Fig 1.). Since that time, an electronic instrument operated by a pressure sensitive magneto-striction pick-up has been used. In the Aviation Method, the temperature effect of operation under knock conditions is used as a basis for the comparison of fuels, while the Supercharge Method relies on aural assessment of knock.

Until 1946, it was the practice to use secondary reference fuels; principally because of limited availability and cost of certified primary reference fuels, however with better purification of hydrocarbons and processes leading to greater availability and lower costs, the certified primary reference fuels have been in common use by engine test laboratories since that time.

# Aviation Gasoline and Supercharged Engines

The requirement for aircraft engines to use a supercharger revealed the inadequacy of testing fuels in normal carburetted engines (not- supercharged). This led to the development of the CFR F-4 Supercharged Method for Aviation Gasoline. One of the obvious technical points was that fuels were developed which exceeded 100 Octane, while the Octane Number Scale was 0 to 100. The problem of greater than 100 Octane was solved by comparison with Iso-Octane with a specified level of Tetra Ethyl Lead (TEL).

For the supercharged engine test a new scale called the Performance Number (PN) which was based on the formula:

PN=2800/(128-ON)

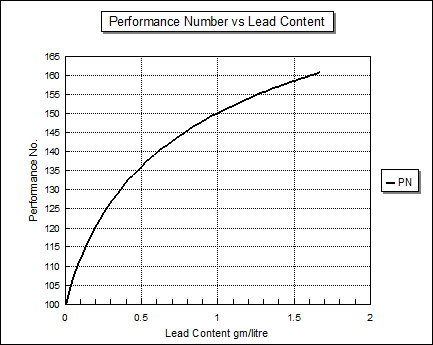
For octane number under 100, such as for Aviation Gasoline 80/87 (where ‘80’ refers to the Lean Rating as Motor Octane Number (MON) obtained from the F-2 test engine (previously F-3 test engine until 1968), and ‘87’ refers to the Rich Mixture Knock Rating obtained from the F-4 supercharged test engine).

Graph 2. Performance Numbers below 100.



For ‘Octanes’ above 100, the comparison is made with leaded iso-octane. For Aviation Gasoline 100/130 (where ‘100’ refers to the Lean Rating as Motor Octane Number (MON), and ‘130’ refers to the Performance Number obtained from the F-4 supercharged test engine).

Graph 3. Performance Numbers above 100



With the ability to manufacture the different grades and specifications and test accordingly, the need arose to distinguish the various grades of aviation gasolines. This was done using dyes at trace levels with various colours used to distinguish the grades. This also identified the maximum lead content, and the minimum octane (and performance number) expected from that fuel.

The grades over the years were:

Table 10. Avgas Grades – Lead, Octane & Colour

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Lean Rating F2 (F3) MON | Rich Rating F4 (PN) | TEL cc/USG | Lead (Pb) gm/L | Colour | Comments |
| 73 | *-* | 0.0 | 0.0 | Clear |  |
| 80 | *87 PN* | 0.5 | 0.14 | Red |  |
| 91 | *96 PN* | 2.0 | 0.56 | Blue | F4 became 98 PN in 1968, obsolete by 1975 |
| *100 PN* | *130 PN* | 3.0 | 0.84 | Green |  |
| *108 PN* | *135 PN* | 3.0 | 0.84 | Brown | Civil aviation |
| *115 PN* | *145 PN* | 4.6 | 1.28 | Purple |  |
| *100 PN* | *130 PN* | 2.0 | 0.56 | Blue | Low Lead Avgas |

# Octane Numbers, Performance Numbers and Grade Nomenclature[[9]](#endnote-9)

All aviation gasolines are known by a grade name with the following general form:

Grade Nomenclature

Aviation Fuel, Grade ‘a/b’, where ‘a’ and ‘b’ are numbers referring to the weak mixture knock rating and the rich mixture knock rating of the aviation gasoline respectively. Some of the earlier lower grades had only one number, that represented by the ‘a’, for the reason that engines which use lower grade gasolines (i.e. straight-run gasolines such as 87 octane and lower) are either un-supercharged or very lightly boosted. Under these conditions, the margin between the operating power of the engine and the power as limited by detonation will be the smallest at weak mixtures and will increase as the mixture strength is richened, this is true whatever the shape of the mixture response curve of the gasoline, and therefore for these gasolines it is necessary to specify weak mixture rating only. For example, Grade 73, however for other grades the nomenclature is – Avgas 91/98, Avgas 100/130, and Avgas 115/145.

While this was the case from the introduction of the rich mixture knock rating, as the importance of aviation gasoline fuels became less in the 1980’s, and the introduction of the new low lead grade called ‘Avgas 100LL’, the practice of including the rich mixture knock rating in the grade name was dropped for this grade specifically, but for the other grades such as Avgas 100/130, the nomenclature practice continued.

Octane Number & Performance Numbers in Grade Nomenclature

According to the British specification in 1948, all knock rating numbers up to 100 were octane numbers, and all numbers above 100 were performance numbers. Also, the method by which the octane or performance number was found was to be specified. For Avgas 91/98, since both numbers were below 100, octane number was denoted in each case. It is perhaps unfortunate that the term octane number use in this case is used to express a rich mixture rating, however it only means that the rich mixture knock performance of the fuel, as expressed in the U.S., is equivalent to that of the reference fuel 98% Iso-octane/ 2% normal Heptane by the standard rich mixture rating test.

In British specifications, the weak mixture knock rating was always specified as an octane number. If this is below 100, two numbers may be quoted, one referring to the octane number found by the Motor Method and the other by the 1-C Method. Hence the importance of specifying by which method an octane number was determined. If the octane number was above 100, it was found by the IP236 Motor Method. This number did not agree with the weak mixture knock rating of the grade name because this is a performance number. For example, Avgas 115/145, the British specification specifies a weak mixture knock rating of 107 octane number by the IP236 Motor Method, whereas the grade name is 115 (which is a performance number).

# Waukesha CFR Engines

Waukesha Engine Company has been designing and producing fuel rating equipment since 1931. For gasoline products there are three CFR Fuel Rating models recognized worldwide for producing consistent, accurate test results in determining the combustion characteristics of motor gasoline and aviation gasoline according to ASTM test method standards.

The versatile CFR Fuel Rating Units are used extensively by petroleum refiners, research laboratories, engine manufacturers, government agencies and universities for a variety of applications including: certification of product quality, fuel and additive technology development, regulatory monitoring of fuel quality, and research and instruction on internal engine processes.

Waukesha Engine offers a complete system for octane determination, CFR Octane Rating Models:

CFR F-1 (Research Method) conforming to ASTM D2699 (ISO 5164) Research Standard Test Methods for Octane Number of Spark-Ignited Engine Fuel.

CFR F-2 (Motor Method) conforming to ASTM D2700 (ISO 5163) Motor - Standard Test Methods for Octane Number of Spark-Ignited Engine Fuel.

CFR F-4 Supercharged Method Aviation Gasoline Rating Unit. The Waukesha F-4 Supercharged Aviation Gasoline Fuel Rating Unit conforms to ASTM D909 (IP Method 119) Standard Test Method for Knock Characteristics of Aviation Gasoline by the Supercharged Method. This method is accepted worldwide as the standard for determining the octane quality of aviation gasoline and aviation gasoline blending components.

CFR Engines Inc. N8 W22577 Johnson Drive, Pewaukee, WI 53186, USA

# Knock Rating as a Function of Hydrocarbon Structure [[10]](#endnote-10)

The relationships between structure and knocking behaviour are not rigid and exceptions appear. Although the general tendencies apply under all engine conditions, the smaller differences depend on the method of evaluation.

Paraffins

In a homologous series the knock rating decreases as carbon atoms are added to the longest straight chain. The effect is large, covering nearly the full range of known ratings. As can be seen for example the MON for n-Pentane is 63.2, while n-Hexane is 26 MON, and of course n-Heptane is 0 MON (the benchmark of zero in the ‘Octane Scale’).

Among the isomers the knock rating increases as the number of the side chains increases. This effect, too, is very large, more than spanning the full octane number scale. Adding side chains in such a way as to increase compactness or centralization raises the rating most. Neopentane is an exception, it is worse than isopentane under all test conditions. If a Methyl group is added to a given paraffin and it introduces an added branch, it usually raises knock rating. The effect is larger if the Methyl is added nearer the centre of the chain.

For example, the MON for iso-Heptane (2-Methyl Hexane) is 46.4 MON, with 3-Methyl Hexane is 55.0 MON, while 2,2-Dimethyl Pentane is 95.6 MON. If this is extended to 2,2,4 Trimethyl Pentane the MON is 100.0 (the benchmark of 100 on the ‘Octane scale’), while 2,3,4 Trimethyl Pentane has a MON of 95.9. The paraffins are the hydrocarbons least sensitive to engine conditions.

Aliphatic olefins

The effects of chain length and chain branching described for paraffins apply for olefins. Among straight chain olefins, the effects of chain length are less than with paraffins. Ethylene is exceptionally poor; Ethylene and Propylene rate below the corresponding paraffins, while C5 and higher olefins rate above the corresponding paraffins. Among straight chain olefins, knock rating increases as the double bond is moved toward the centre of the molecule. Introduction of a double bond in a branched paraffin raises the knock rating for slightly branched paraffins but lowers the rating for highly branched hydrocarbons. Centralization of the double bond in branched olefins tends to raise knock ratings. Introduction of a double bond in a paraffin has more tendency to raise knock rating if it is added next to the Methyl group in a mono-methyl paraffin or near the quaternary carbon in a dimethyl paraffin. Cis-Trans isomers rate alike. Aliphatic olefins are much more sensitive to engine conditions than the corresponding paraffins except at low knock ratings. However due to their inherent reactivity, olefins are usually not preferred directly as an ingredient in gasoline blendstocks, but rather to be polymerised into highly branched paraffins by the alkylation process. Olefins can be unstable and form gum deposits which is undesirable.

Cyclopentanes and cyclohexanes

These naphthenes cover generally the same knock rating range as the paraffins, naphthenes rate better than corresponding n-paraffins, although none are as good as the best branched paraffins. For example, n-Hexane has 26 MON, Cyclohexane has 77.2 MON, while 2,2 Dimethyl Butane has 93.4 MON.

Adding a straight side chain lowers knock rating. The effect increases with chain length. Branching in a side chain of given length raises knock rating. Change from one straight side chain to two at given molecular weight raises the rating. This is illustrated by Methyl Cyclohexane which has 71.1 MON, Ethyl Cyclohexane has 40.8 MON, but 1,1 Dimethyl Cyclohexane has 85.9 MON.

Among two-branched cyclohexane isomers, the order of decreasing knock rating tends to be:

1, 1 > (1, 2-) > (1, 3-) > (1, 4-), and Cis > Trans configurations.

The cycloparaffins are more sensitive than the paraffins. Sensitivity is greater at high knock ratings.

Aromatics

The aromatics have high knock ratings, usually above 100 octane number. Adding a straight side chain to Benzene lowers knock rating. The effect increases with chain length. As an exception, Ethyl Benzene falls below n-Propyl Benzene by most methods. Branching in a side chain of given length raises the knock rating e.g. 3o Butane> iso-butane > 2o Butane > 1o Butane.

Change from one straight side chain to an isomer with two chains meta or para to each other raises knock rating. Di- or Polysubstituted benzenes with groups in the ortho or 1,2 position have unusually low ratings. Most aromatics are highly sensitive to engine conditions. They vary markedly in sensitivity.

Miscellaneous

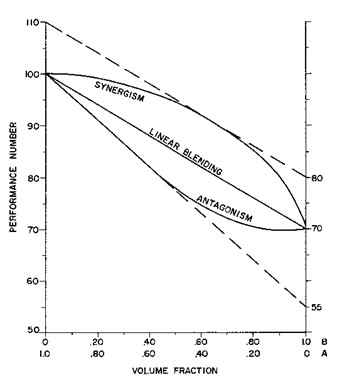
Diolefins are superior to the corresponding paraffins (with exceptions). Conjugation of double bonds raises the rating. Acetylenes vary widely in knock rating relative to the corresponding paraffins. Acetylene is very bad. Centralization of the triple bond raises the rating. Monocyclic olefins and diolefins rate below the corresponding saturates. Double bonds in side chains of aromatics may raise or lower ratings. These are generally not encountered in gasolines due to their reactive nature, or conversion in the alkylation process.

With the establishment of the Octane scale, the next step for the petroleum chemist and engineers was to attempt to predict the octane of any particular hydrocarbon mixture. It was quickly discovered that octane ratings of individual components did not blend linearly and that some blends showed ‘synergism’ while others show ‘antagonism’. Refer to Figure 5.

Blending Octane Numbers

To overcome this problem of uncertainty in blending, Blending Numbers were developed to predict how the particular component would behave when calculated in a linear blending method. For example, n-Hexane the MON Blending Octane Number is 22 (compared to its MON of 26), while Cyclohexane is MON Blending Octane Number of 97 (MON of 77.2), and Benzene has a MON> 100 with a MON Blending Octane Number of 91.

Figure 4**.** Performance Number versus Volume fraction



For the compounds other than hydrocarbons these blending octane numbers can be dramatic such as n-Methyl Aniline has a MON Blending Octane Number of 411 and hence its attraction as a blending additive for use in 150 PN Avgas by the British Spitfires and Hawker Tempests to chase the German V-1 Flying bombs.

# Epilogue for Octane

By the start of the 1930’s the “Octane Scale” was established, and the word and meaning of ‘Octane’ would become part of world’s everyday lexicon.

New laboratory test engines were developed to test the fuels against this Octane Scale. Eventually the laboratory test engines would be reduced to just three types to cover the octane testing of motor gasolines and aviation gasolines. These engines would be used universally around the world, and would be manufactured by only one company – the Waukesha Engine Company, now known as CFR Engines Inc.

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